

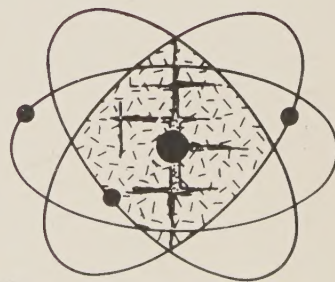
STRIAE

CHARACTERISTIC FEATURES OF A SUPERFICIAL ROCK MASS IN SOUTHERN CENTRAL SWEDEN –

Horizontal and Subhorizontal Fractures
and Filling Material

ANDERS CARLSSON

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CHARACTERISTIC FEATURES
OF A SUPERFICIAL ROCK MASS
IN SOUTHERN CENTRAL SWEDEN —
Horizontal and subhorizontal fractures and filling material

By

Anders Carlsson
fil. kand., värml.

Doctoral dissertation

to be publicly discussed in the lecture hall of the Institutes of Geography and Geology of the University of Uppsala on January 17, 1980, at 10 a.m. for the Degree of Doctor of Philosophy (according to the Royal proclamation No. 327, 1969).

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CHARACTERISTIC FEATURES OF A SUPERFICIAL ROCK MASS IN SOUTHERN CENTRAL SWEDEN — Horizontal and subhorizontal fractures and filling material

ANDERS CARLSSON



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A characteristic feature of the uppermost rock mass in the Forsmark area is the occurrence of horizontal and subhorizontal fractures, most of them filled with sediments. The frequency of these fractures, the causal connection of the wide fracture apertures, and the occurrence and behaviour of filling material will be discussed. For this purpose a joint survey was carried out and significant fracture data thereby obtained. Results from geological and geophysical explorations were used in order to envisage the geological and tectonic conditions, while studies of rock mechanics allowed the evaluation of the present stress situation of the rock mass. Most of the horizontal and subhorizontal fractures are believed to develop from potential fractures due to high horizontal stresses, and expansion of fracture apertures, which may permit the penetration of sediment, possibly in consequence of changes of the stress situation during the last deglaciation.

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Introduction

A most striking feature of the gneiss granitic rock mass at Forsmark in the north-eastern Uppland (Fig. 1) is the difference in fracture behaviour between the uppermost part of the rock mass and deepseated masses. Generally speaking, the actual difference is the occurrence of superficial horizontal and subhorizontal fractures with wide apertures most of them filled with unconsolidated sediments and rock fragments.

The horizontal and subhorizontal fractures in the superficial rock mass at Forsmark may be described as a structure found primarily in granitic rocks which is commonly termed sheet structure, defined by Dale (1923:26) as the division of granite into sheets or beds by jointlike fractures which are variously curved or nearly horizontal, and generally parallel with the granite surface. Both continuous

and discontinuous horizontal fractures in the Forsmark area running almost parallel to the rock surface divide the rock mass into sheets or slabs of varying thickness. As will be described, the horizontal and subhorizontal fractures occur independently of all other discontinuities in the rock mass.

In this paper, the terms horizontal fracturing, horizontal and subhorizontal fractures are consistently used to describe the flat fractures in the rock mass. Differences and similarities between the horizontal fractures in the Forsmark area and sheet or flat-lying fractures described in the literature are here discussed. However, it must be emphasized, that descriptions of fractures made by other authors are used to demonstrate a similarity to the Forsmark fractures. Hence, the comparison should not be

regarded as a form of extrapolation from one type of fracture to another, but is purely made for the purpose of description.

A number of theories concerning the origin of fractures parallel to the land surface are reported in the literature exhaustively so in Dale (1923), Jahns (1943), Soen (1965) and Twidale (1973) wherefore only a brief review is given here.

Sheet jointing due to insolation and other variations in temperature was suggested by inter alios Shaler (1869), Macmahon (1893) and Merrill (1906). Intense heat from forest fires caused exfoliation which was demonstrated by e.g. Högbom (1921), Blackwelder (1927) and Emery (1944), while D.C. Barton (1916) reports inter alia disintegration due to rapid temperature changes in deserts. Wolters (1969) asserts that changes in temperature may cause sheet jointing. This theory is based on examinations of rock cores from deep drill-holes, and a change in temperature of 100°C may produce greater strains than the erosion of 10 000 m rock. The author also points out that temperature variations between day and night in temperate zones can result in stresses corresponding to the erosion of several meters. Moreover continual repetition of such strain can cause fracture under minor stresses. Thus such changes in temperature may contribute to the thinner near-surface lamination. Flaking and spalling of rock masses due to weathering were discussed by inter alios Blackwelder (1925, 1933) and Chapman and Greenfield (1949). The hypothesis of off-loading or pressure release was proposed by Gilbert (1904) and later by Farmin (1937), Waters (1954), Lewis (1954), Scheidegger (1963), Soen (1965) and Hack (1966). Some authors, e.g. Vogt (1879) and De La Beche (1839) related sheet structure to plutonic injections while Jones (1859) attributes an inselberg on Dartmoor to metasomatic expansion. Correlation of sheet structure with vertical uplift was discussed by e.g. Bott (1956) and Rowan (1968), and sheet jointing as an expansion of lateral compression suggested by e.g. Dale (1923) and Twidale (1971).

The horizontal and subhorizontal fractures in the Forsmark area and the sediment filling were earlier described by Stephansson and Ericsson (1975), A. Carlsson and T. Olsson (1976b), and O. Stephansson and H. Carlsson (1976, 1977). The fracturing of the superficial horizontal and subhorizontal fractures at Forsmark was also treated by Möerner (1977). In terms of rock hydraulics A. Carlsson and T. Olsson (1976c, 1977a, 1977b, 1979a) discussed the horizontal and subhorizontal fractures at Forsmark.

Forsmark aside, horizontal and subhorizontal fractures filled with sediment materials occurring in the Swedish crystalline bedrock were described by Morfeldt (1962), Morfeldt, Nordin and Roosar (1967), Martna (1972b) and Möerner (1977, 1978). The accounts of Morfeldt (1962), Morfeldt, Nordin and Roosar (1967) and Möerner (1977, 1978) deal with fracturing and sediment fillings in the Stockholm area and southwestern Sweden, while Martna (1972b) reports on such fractures in northern Sweden at the sites of some hydropower plants, namely Boden, and Parki and in the vicinity of Lake Satsjaure. All these descriptions deal with horizontal and subhorizontal fractures occurring in granitic rocks, and also occur in the superficial bedrock. Analyses of the filling material were presented by Stephansson and Ericsson (1975) and by A. Carlsson and T. Olsson (1976b). Ahlberg and Lundgren

(1974), mention the occurrence of sediment filling in fractures close to the bedrock surface as comparatively rare phenomenon.

The genesis, age and preservation of the sediment in the horizontal and subhorizontal fractures at Forsmark were interpreted by Stephansson and Ericsson (1975) which interpretation is here briefly reviewed.

The subhorizontal and vertical sets of joints (the authors refer to subhorizontal joints, but the terms horizontal and subhorizontal fractures are used in the present work) together with strong foliation create a loose structure in the rock mass. In a cold climate, e.g. the end of an interstadial or interglacial period, any water in the joints will freeze. The freezing causes a widening in a vertical direction of the subhorizontal joints and blocks are loosened from the joint surfaces. As the climate becomes colder, an advancing ice is assumed to move over the area, while the joints are still filled with ice. During the following ice recession fine-grained sediments of glaciofluvial type are deposited in the open joints. The occurrence of sedimentary structures, such as graded bedding indicated streaming of water through the open joints. Once again, the ice is assumed to have covered the area. The loading of the ice and the overlying bedrocks causes compaction and dewatering of the sediment. Eventually, during the last recession, till is deposited over the area.

The occurrence of pollen and diatoms in the sediments of the fractures and the overlying till was examined by Stephansson and Ericsson (1975:93). No diatoms were found and, according to Stephansson and Ericsson (1975:93), the pollen flora of the sediment samples implies redeposition of older interglacial or interstadial sediments. This is deduced from the relatively high frequencies of AP, especially high frequencies of *Picea*, *Corylus* and *Alnus*, and according to Stephansson and Ericsson (1975:93), the flora cannot be of Holocene age, since the frequency of QM is low despite high frequencies of *Alnus* and *Picea*. Thus the structure, composition, and the pollen flora of the sediments in the subhorizontal fractures suggest deposition during a Pre-Holocene age, possibly during Early or Middle Weichsel.

Further evidence of the validity of the theory, that the sedimentation occurred during an interstadial or interglacial in Early or Middle Weichselian times was submitted in A. Carlsson and T. Olsson (1976b). The contribution to the theory proposed by Stephansson and Ericsson (1975) derived mainly from compression experiments on the filling material. The compression experiments presented in A. Carlsson and T. Olsson (1976b) indicate that the material was exposed to a pre-consolidation load of about 3400–3900 kN/m². Since a pressure of this magnitude could not have existed in Holocene time, the degree of preconsolidation in the material would seem to support the theory proposed by Stephansson and Ericsson (1975). Stephansson (pers. comm.) points out that the open joints originated through tectonic processes in Weichselian time, and the area of joints with filling is bordered by major fracture zones (cf. Fig. 9). According to Stephansson (pers. comm.) the geological structures and present rock stresses in the block indicate shear movements along the Öregrund-Singö line and the Forsmark-Granfjärden line and development of second-order fractures between these two major fracture zones. The opening of the subhorizontal joints appear in a stress field, limited by the two major fracture zones.



Fig. 1. The geographical position of the investigation area.

Furthermore, Stephansson (pers. comm.) points out that a re-examination of seismograms from marine-geology profiles in the Åland Sea reveals no disturbances in the reflector of the glacial-to-post-glacial boundary, which is considered to be strong evidence of the absence of Holocene movements in the Forsmark area.

Mörner (1978:42) adduces the Bjäre Peninsula in south-western Sweden where the bedrock is said to be so heavily fractured, that it can be excavated with a spade. According to Mörner this fracturing must have taken place at about the time of deglaciation and it must have occurred after the final stage of glacial erosion just inside the ice margin because the loose parts of the fractured bedrock remain in place, but before the deposition of the covering sandy-silty deposits in front of the ice margin because these do not exhibit any sign of fracturing. Mörner (1978:42) also cites the Stockholm area, describing the bedrock as often deeply

fractured with loose blocks at the surface although the bedrock surface is very well polished and grooved by glacial erosion and exhibits numerous striae from the deglaciation phase. According to Mörner (1978:42), the glacial scouring of the bedrock surface indicates that the ice sheared with strong glacial dynamic force over the surface, which would have removed any loose blocks. Therefore the fracturing undoubtedly postdates the glacial erosion, and the fracturing must be due to the rapidly changed stress and strain situation in the bedrock and, or earthquakes initiated by the peak rates of glacio-isostatic uplift (Mörner 1978:42–43). As regards the sediment filling in the Forsmark area, Mörner (1977:11) says, that pollen analysis and compaction cannot be used to determine its age as proposed by Stephansson and Ericsson (1975), but considers the horizontal fracturing at Forsmark may have occurred at about the time of deglaciation.

In the light of almost five years of geological observations at Forsmark, the present paper will deal with some characteristic features in the fracture behaviour of the uppermost part of the rock mass. The study was performed as part of a research program at Civil Engineering Development of the Swedish State Power Board. The main purpose of the research program was to collect, process and analyse geological data from different areas of construction in order to devise a safe and efficient design. The present work is based chiefly on geological investigations carried out during construction, such as underground mapping, and surveys in excavated shafts, but also in large measure on results from geological and geophysical explorations and rock mechanical studies made in the area.

The thesis attempts to describe characteristic features of the superficial rock mass at Forsmark, primarily regarding the frequency of horizontal and subhorizontal fractures, the causal connection of the wide apertures of those fractures and finally, the occurrence and behaviour of the filling material.

Investigation area

Site

Forsmark Power Station is situated on the east coast of Sweden in north-eastern Uppland in Östhammar municipality, about 130 km north of Stockholm (Fig. 1). The towns of Öregrund and Östhammar are situated about 20 km south-east of the power station, and the nearest village is the old Forsmark Estate, some 5 km to the south.

The Power station stands on the coast about 500 m from the sea, the Gulf of Bothnia, the extent of the main construction area being illustrated in Fig. 2. The artificial biotest lake can also be seen together with various roads and a harbour, which was constructed for large and heavy transports to and from the plant. The topographical maps which cover the Forsmark area are 12 I Östhammar NE and 13 I Österlövsta SE and the geological maps are SGU Ser Aa No 98 and 99 with a description by Svenonius (1887).

The Forsmark Power Station

The Forsmark Power Station is built and shall be operated

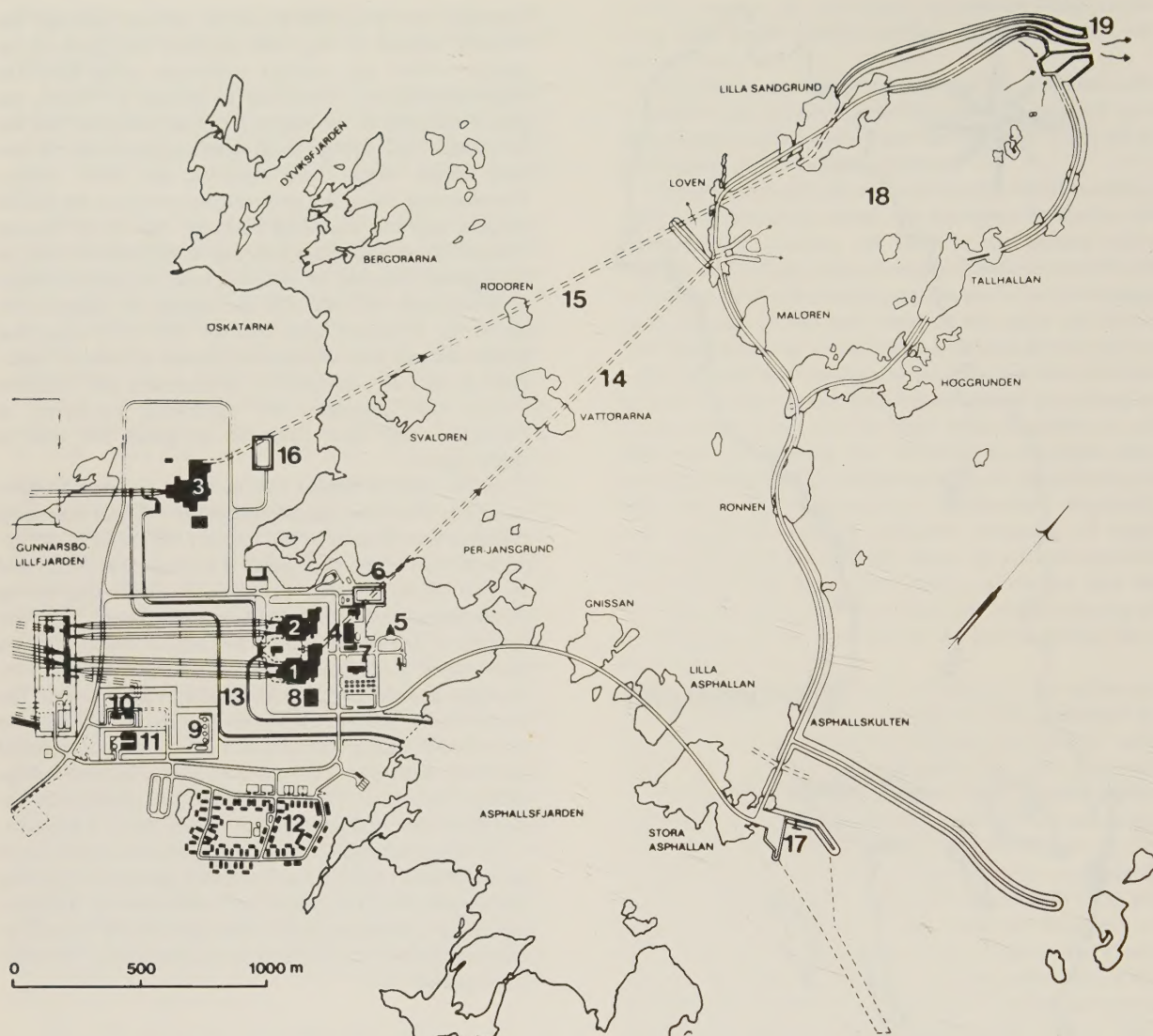


Fig. 2. Site plan of the Forsmark Power Station. 1. Unit 1. 2. Unit 2. 3. Unit 3. 4. Store and workshop. 5. Water tower. 6. Surge basin. 7. Utility building. 8. Waste handling plant. 9. Oil store for gas turbine. 10. Gas turbine plant. 11. Storage basin for industrial water. 12. Housing area. 13. Inlet channel. 14–15. Discharge tunnels. 16. Surge basin. 17. Harbour. 18. Biotest lake. 19. Cooling water discharge.

by an incorporated company, Forsmark Kraftgrupp AB, which is owned by the Swedish State Power Board, and Mellansvensk Kraftgrupp AB. Forsmark Kraftgrupp AB has commissioned the Swedish State Power Board as a general contractor of the plant.

The station is a nuclear power plant, two units being complete and ready for operation and one under construction. The units are boiling water reactors of light water design; the first two which are identical each have a net output of 900 MW while the third is somewhat larger and will have a net output of 1000 MW. Each of the Forsmark units requires approximately 40–50 m³ cooling water per second; sea water will be used for this purpose wherefore an inlet channel has been excavated. The heated cooling water is then discharged through two sub-marine tunnels into the sea. The temperature of the cooling water will be about 10°C higher than that of the sea water. The total building volume of the three units is about 2 million m³ of which the reactor building with reactor containment and

the turbine building stand for about 50 per cent of the total building volume.

Construction work

All three units are founded on rock with a depth of foundation of about 5–20 m. Due to excavation of shafts for the units and excavation of the inlet channel, discharge tunnels, headrace tunnels, open culverts and so forth, the rock excavation has been of considerable dimensions. The quantity of rock hitherto excavated amounts to about 1 million m³ and a further 1 million m³ of Quaternary deposits have been excavated in the area.

The 2300-m-long discharge tunnel of Units 1 and 2 runs from the station area via a surge basin to discharge at Loven Island, Martna (1978). As shown in Fig. 2, for most of its length the tunnel runs underneath the Gulf of Bothnia. The cross sectional area of the tunnel is about 80

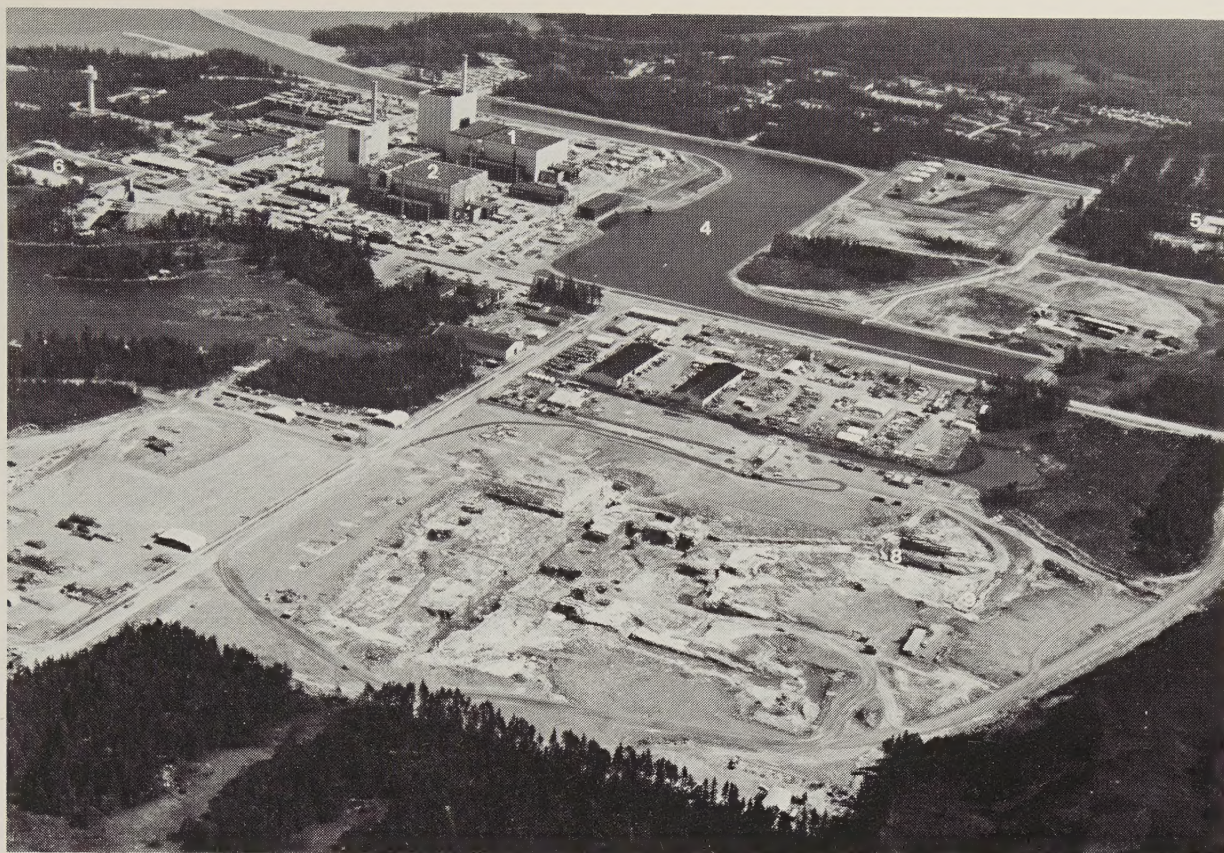


Fig. 3. Aerial photograph of the Forsmark area. 1. Unit 1. 2. Unit 2. 3. Unit 3. 4. Inlet channel. 5. Storage basin for industrial water. 6–7. Surge basins. 8. Headrace tunnel. 9. Recirculation tunnel. Photograph by Göran Hansson/N.

m² and the tunnelling was carried out both from the mainland and from Loven Island with a top-heading of about 50 m² and a bench of 30 m². The tunnel is about 75 m below sea level, the rock cover being approximately 55–60 m thick. The discharge tunnel of Unit 3 is at present under construction. The excavation of the tunnel for Unit 1 and 2 was continuously followed by a geological survey, for the purpose of obtaining information about geological and tectonic conditions in the rock mass and hydrogeological data on the water leakage in the tunnel (A. Carlsson and T. Olsson 1976a and 1977a). The geological mapping has also provided information on the occurrence of horizontal fractures far below the rock surface. The discharge tunnel is thus the deepest site examined.

A so-called biotest lake, some 90 hectares in size connected with the outlet of the discharge tunnels was constructed in order to allow investigation of the effect of the discharge of the heated cooling water on marine-flora and fauna. The dam incorporates material from the earth and rock excavation in the area.

Investigated area

The present work is based on results of geological investigations almost throughout the area shown in Fig. 2, but the results of investigations on the mainland will mainly be used here (Fig. 3). However, in order to visualize the local geological and tectonic conditions results of geological mapping on the islands have been used as well

as results of drillings throughout the area of Fig. 2, concentrating on the sites of the Forsmark units.

Detailed investigations were made in the 1921-m-long section of the discharge tunnel of Unit 1 and 2 between the surge basin and Loven Island. These are particularly valuable as the tunnel intersects tectonic zones and also penetrates the rock boundary. However, the work is chiefly based on studies on the excavated shafts in the area while the most detailed examination was made in the shafts of Unit 3. Figure 4, represents a general view of the investigated area at Unit 3. This area cover about 50 000 m². Observations were also recorded in the headrace tunnel, discharge tunnel and the recirculation tunnel of Unit 3. Furthermore, investigations were carried out in the shafts of the storage basin for industrial water, the inlet channel, the surge basins of the units and in the shafts of Unit 2. Samples of sediment fillings were collected from the storage basin for industrial water, the inlet channel and the turbine building site at Unit 1. However, most of the samples of the sediment fillings and of the till were collected from the area of Unit 3.

Geological site investigations

Geological and geophysical explorations

The geological and geophysical explorations were started in 1971 and have been in progress ever since (Larsson 1973, 1975, Larsson and Moberg 1974, 1975). The con-

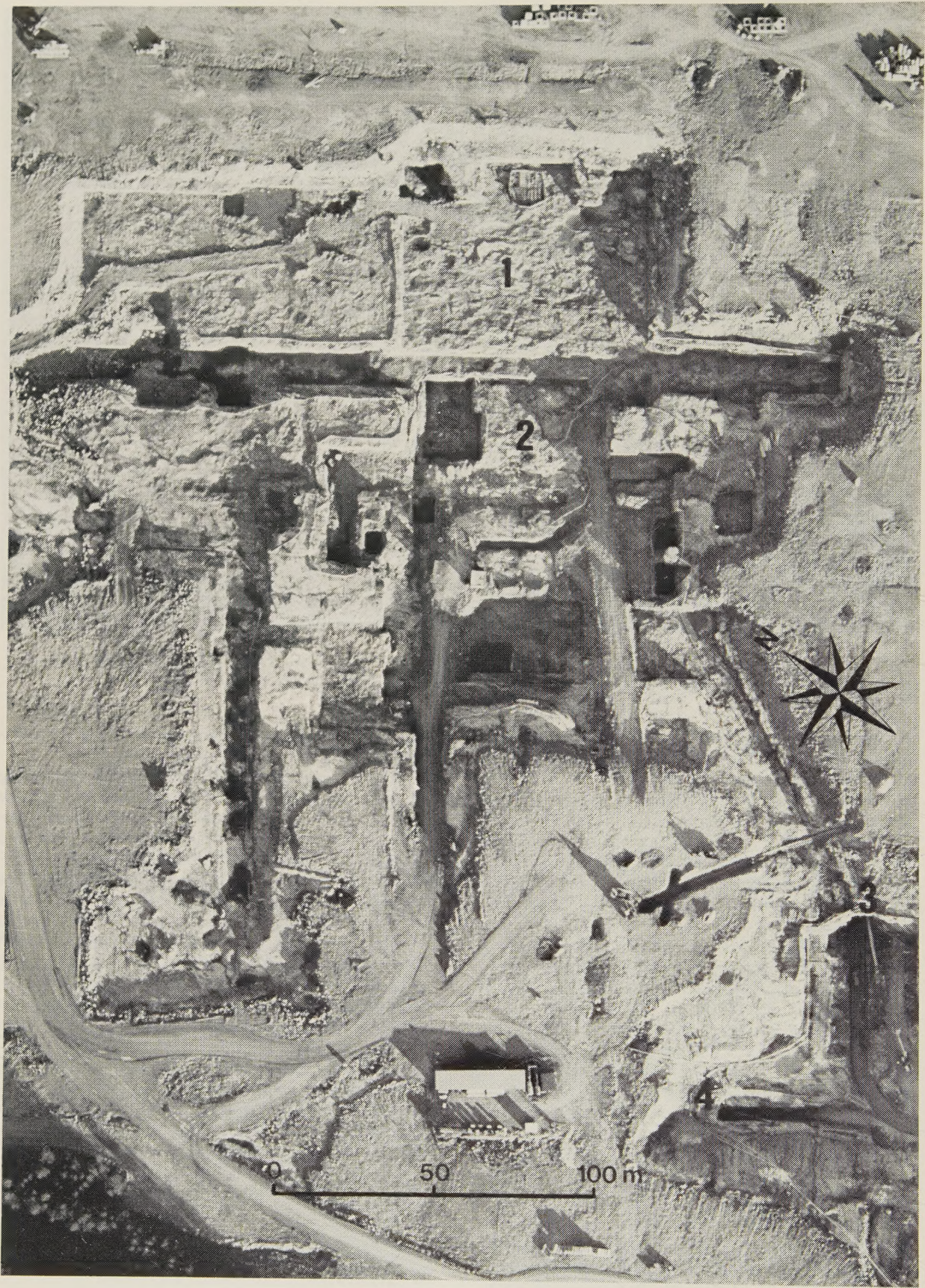


Fig. 4. Aerial photograph of the investigation area at Unit 3. 1. Site of the reactor building. 2. Site of the turbine building. 3. The initial point of the headrace tunnel. 4. The initial point of the recirculation tunnel. Photograph by Göran Hansson/N.



Fig. 5. A view of the area of Unit 3 before the forestry work was done showing the topographical features to the southwest of the Forsmark plant. The building in the foreground is the construction office. Photograph by Göran Hansson/N.

tinuity of exploration is a consequence of the dimension of the units and the special requirements for the foundations.

The explorations for the Forsmark Power Station include both regional and detailed investigations, which were undertaken simultaneously. The regional investigations were started with a review of earlier geological studies made locally together with other appropriate material such as topographical maps and aerial photographs. These investigations were then supplemented by a geological survey to elucidate the regional stratigraphy and the local rock distribution and discover whether any zones of weakness exist. This latter part of the investigation was first performed on rock outcrops within the area.

Detailed studies were then instituted, first with a net of seismic profiles whereupon the zones of weakness indicated by the regional and seismic investigations were closely examined by rock drillings. The seismic investigations were then intensified, further nets of seismic profiles being made, and the intensity of rock drilling likewise increased. In addition, trenches in the rock mass were excavated and closely examined.

In all, about 100 km of seismic profiling has been carried out in the Forsmark area, primarily to identify zones of weakness in the rock mass, but also to provide information on the cover of the Quaternary deposits. Zones of weakness indicated by the seismic measurements could then be verified by rock drillings and to date, about 10 km rock drilling have been carried out. In a great number of the drill-holes, water pressure tests have been made in order to obtain a measure of the tightness of the rock mass.

The results of all of these investigations made the basis of the final location of the Forsmark units.

Site investigation during construction

In situ determination of the deformation characteristics of the rock mass, and in situ rock stress measurements were carried out primarily during construction (Hiltscher and Strindell 1976a, 1976b, 1976c, 1976d). A number of ground water studies were also made in the area in the course of construction. The purposes of these studies differ somewhat with various types of planning and working methods in mind. The site investigations mentioned here will be described and discussed later on. Apart from the above investigations, this study is largely based on a joint survey carried out in the excavated shafts within the construction area. The most detailed survey referred to Unit 3 and the planning and the working method of this survey will be described separately later. Furthermore, a number of laboratory investigations were performed which will be presented together with the results.

Geology

Morphology

From a morphological point of view, the Forsmark area is remarkably flat with minor topographical variations. Lundqvist (1958:73) points out that in the mire region of



Fig. 6. Sketch map of the geology in northeastern Uppland. 1. Gneiss granite. 2. Paragneiss. 3. Granite. 4. Alkaline rocks. Modified after Welin (1964:52).

northern Uppland, the flatness is so marked that the area could be designated a peneplain. The slight differences in elevation in northern Uppland were also described by e.g. Gillberg (1967:39).

The ground level of the investigated area lies about 1 m above sea level. A rather flat depression in the ground-surface running north-south crosses the investigation area of Unit 3 and is also reflected in the rock surface. After excavation of the Quaternary deposits, the differences in level of the bedrock surface proved to be twice as great as the variation in the ground level. Consequently, the soil cover in the area of Unit 3 presents a topographical compensation effect. During the geological and geophysical exploration of Unit 3, this topographical effect was also demonstrated by Larsson (1975:1). The bedrock surface in the area of Unit 3 lies about 3 m below sea level and in the adjacent area, it is situated approximately at sea level. Moreover, the ground surface here lies on a somewhat higher level than that of Unit 3, about 1.5 m. These altitude

data concerning both the ground level and the rock surface are derived from seismic investigations, drillings and levelling measurements.

About 2.5 km to the west of the investigation area, altitudes of 25 m above sea level are occasionally found but it is necessary to go about 15 km westward from Forsmark to find a more continuous altitude of 20–30 m above sea level. Fig. 5 illustrates the topographical features in the vicinity of the Forsmark Plant.

Bedrock

The bedrock of northern Uppland is described by inter alios Sund (1957) and Welin (1964) as consisting of a complex of Svecofennian supracrustal rocks. A sketch map of the geology in north-eastern Uppland is shown in Fig. 6. According to Welin (1964:53), the rock is composed of granites and heavily metamorphosed supracrustal rocks



Fig. 7. Amphibolitic greenstones and pegmatites forming dikes and isolated fragments in the gneiss granite on the western shaft wall of the inlet channel. The length of the ranging pole is 4 m. Photograph by Göran Hansson/N.

while lower parts of the supracrustal series are mainly built up by volcanic rocks, arkosic material dominate on the higher levels. Welin (1964:53) describes the bedrock of northern Uppland as consisting of largely synkinematic granites, volcanic rocks and migmatites. Veined gneisses have not been formed but locally the bedrock is cut by late-kinematic granites and pegmatites. Sund (1957:6) points out, that the pegmatite is primarily concentrated in northern and north-eastern Uppland. The area also consists of fine-grained leptytes and in the northernmost part of the area shown in Fig. 6, the leptytes have been granitized and, according to Sund (1957:6), also been transformed to vein gneisses. The oldest Archean granites have generally preserved their primary massive structure but according to Sund (1957:21), the granites in the marginal areas are foliated and may be designated gneiss granites. The gneiss granite in the Forsmark area is an example of such a granite. The basic rocks, greenstones, penetrate the oldest Archean granites as dikes, massifs, veins and lenses and the pegmatites intersect the granites as dikes, massifs and intrusions. The greenstones appearing as dikes or bands in the northern and eastern part of the area can be characterized according to Sund (1957:21) as a schistose amphibolitic greenstone of basalt type and porphyritic greenstone.

According to a subdivision of the Svecofennian of Central Sweden into subprovinces and batholiths (Stephansson 1975:201), the area is characterized by granitic gneisses, migmatites, metasediments and metavolcanics with occurrences of pegmatites. O. Stephansson and H. Carlsson (1976:73) point out, that the pegmatites are associated

with the intrusion of the serogenic granites which form massifs to the east and to the west of Forsmark.

The bedrock within the area of the Forsmark Plant is described by Larsson (1973, 1975), and briefly also by O. Stephansson and H. Carlsson (1976), and by A. Carlsson and T. Olsson (1976b, 1977a, 1978b). The bedrock consists of old Svecofennian, schistose, intrusive rocks of tonalitic composition, so-called gneiss granites as well as mica gneisses and mica schists, here termed paragneisses. The acid-to-intermediate gneiss granite has a rather well defined schistosity and anisotropy, and the general direction of foliation is northwest-southeast with a steep dip direction to the northeast. The paragneiss in the area is fine-grained in texture with a well defined parallel structure. Veins of quartz and feldspar in the paragneiss run parallel to the rock foliation, and the foliation of the paragneiss as well as the foliation of the gneiss granites strikes northwest to southeast and dips steeply to the northeast. The rock contact of the gneiss granite and the paragneiss could be seen in the discharge tunnel about 1500 m out from the surge basin and can also be seen at Stora Asphällan Island. The rock boundary runs approximately in a direction of northwest to southeast; i.e. parallel to the foliation of the two main rock types. In the paragneiss, dikes of amphibolitic composition run parallel to the foliation plane of the rock. In the gneiss granite, the amphibolitic greenstones form dikes and isolated bodies. Schistose greenstones of basalt type occur in the Forsmark area. Some remnants of leptyte, acid-to-intermediate, fine grained gneisses of volcanic origin, may also be found in the gneiss granite, and late Svecofennian dikes and small

massifs of pegmatite make up about 10 per cent of the rock.

Due to tectonic movements, mylonitic rocks and breccias have developed across a 200-m-wide zone which intersects the tunnel about 1300 m out from the surge basin. In this brecciated gneiss granite, there are numerous veins of quartz and calcite, and several clay-filled fractures with a maximum width of about 50 cm appear within the brecciated zone. The material was identified by X-ray diffraction as being chiefly illite and quartz. Several calcite veins, partly forming druse cavities with crystallizations of calcite and aragonite and pyrite, are also to be found in the zone.

In Fig. 7, the characteristic nature of greenstones and pegmatite in the gneiss granite is shown and a quantitative description of the rock distribution within the area of Unit 3 is given in Fig. 8.

Tectonic features

Forsmark Power Station is situated between two major fracture zones with a strike direction of northwest to southeast and steeply dipping. The intervening rock mass demarcated to the north and south shows evidence of a second order tectonization which probably has occurred during the movements of these major fracture zones. This fracture tectonization has resulted in a number of second order fracture zones which have a general strike direction of north to south. The fracture tectonization is illustrated in Fig. 9, in which the two major fracture zones and the second order intervening fracture zones are indicated.

During the excavation of the discharge tunnel of Units 1 and 2, the northernmost major fracture zone was subjected to detailed survey (A. Carlsson and T. Olsson 1976a:7, 1977a:10–13). The width of the zone is about 200 m. According to Larsson (1973:4–5), the post-orogenic tectonization of the rock took place during at least six separated phases, with intermediate calcite and quartz dissemination of the crushed rock. Figure 10, illustrates the brecciated gneiss granite with its numerous veins of quartz and calcite. The frequency of open fractures within the brecciated zone greatly increases along a 50 m section and clay-filled fractures are seen (cf. Fig. 11), while the remainder of the zone shows very tight fractures. The southernmost major fracture zone is of similar width. No detailed investigation was made of the southernmost zone but a seismic profile which crosses the fracture zone indicates a low seismic velocity (3000–4000 m/s). Drillwells for water supply purposes were drilled in the zone, and the result indicates a comparatively high frequency of fractures.

The major fracture zones probably have similar interior structure owing to the 5 km separating them, but also because the same main rock type predominates throughout. Therefore it is reasonable to assume, that the southernmost major fracture zone too is partly healed and clay mineralization occurs. As mentioned earlier the tectonization of the intervening rock mass is probably related to the movements of the major fracture zones. The strike directions of the steeply dipping second order zones indicate their possible development as shear zones in connection with compression of the rock mass, although the initial development may have other causes.

One of the second order zones intersects the tunnel

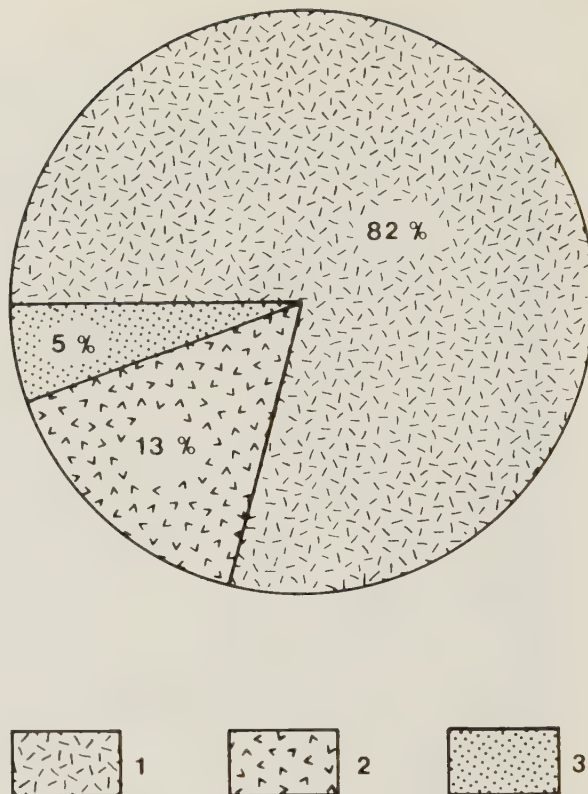


Fig. 8. A quantitative description of the rock distribution within the area of Unit 3. 1. Gneiss granite. 2. Pegmatites. 3. Greenstones.

wherefore this zone was closely examined. The strike direction of the zone is N80°W which excludes it from the secondary system, which seems predominant in the area with a strike direction of N–S and a strike tendency of NW–SE. In the tunnel the width of the zone is approximately 50 m, with a high frequency of open fractures and some clay mineralization.

In contrast to the complicated tectonics of the northernmost major fracture zone with various phases of tectonization, only one phase could be observed in this second order zone. Like the other steeply dipping fracture zones, it probably developed in connection with compression of the rock mass during some of the different phases of tectonization in the major fracture zones. The two major fracture zones have also been indicated by interpreting aerial photographs taken from the Landsat satellites (Ehrenborg and Stephansson 1976). Marine-geology studies in the Åland Sea have shown a southeastern continuation of the two major fracture zones and a total length of the two zones of about 60 km (Flodén 1973).

There is a distinct difference in joint pattern between the two main rock types in the area in that the fracture planes of the paragneiss correspond in general to the schistosity of the rock, while the gneiss granite shows a blocky structure. The paragneiss has a chiefly slaty structure with steep fractures split into smaller blocks. The gneiss granite shows an orthogonal joint pattern with a strike direction which is in fairly well close agreement with the direction of the foliation namely NW–SE and a strike maximum perpendicular to the foliation, NE–SW (Fig. 12).

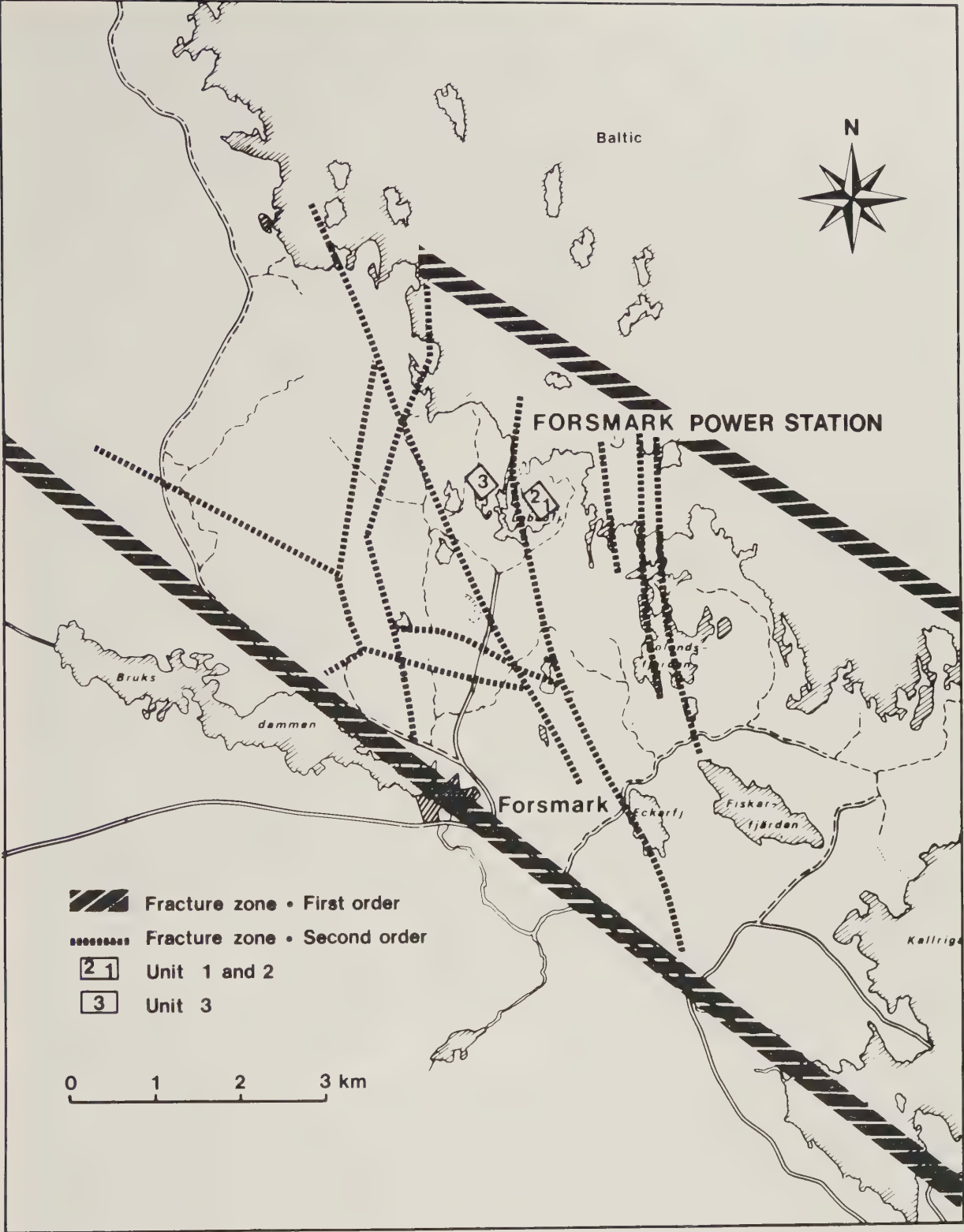


Fig. 9. Main tectonic structures in the area of the Forsmark Power Station.

Quaternary deposits

Almost throughout the whole investigation area, the bedrock is covered by Quaternary deposits mainly consisting of till and peat deposits and therefore rock outcrops

on the mainland are of rare occurrence. Till is the predominant Quaternary deposit with a mean cover of approximately 3–5 m and a maximum value of 14 m. A



Fig. 10. Brecciated gneiss granite with numerous veins of quartz and calcite representing a 4 m-section on the eastern tunnel wall in the northernmost major fracture zone observed in the discharge tunnel of Units 1 and 2. Photograph by Göran Hansson/N



Fig. 11. A clay filled fracture within the northernmost major fracture zone observed in the discharge tunnel of Units 1 and 2. The fillings have been removed prior to sealing with concrete. The light area in the upper part of the rock wall is shotcrete. Photograph by Goran Hansson/N.



Fig. 12. The blocky structure of the gneiss granite showing a rather well developed orthogonal joint pattern. Photograph by Göran Hansson/N.

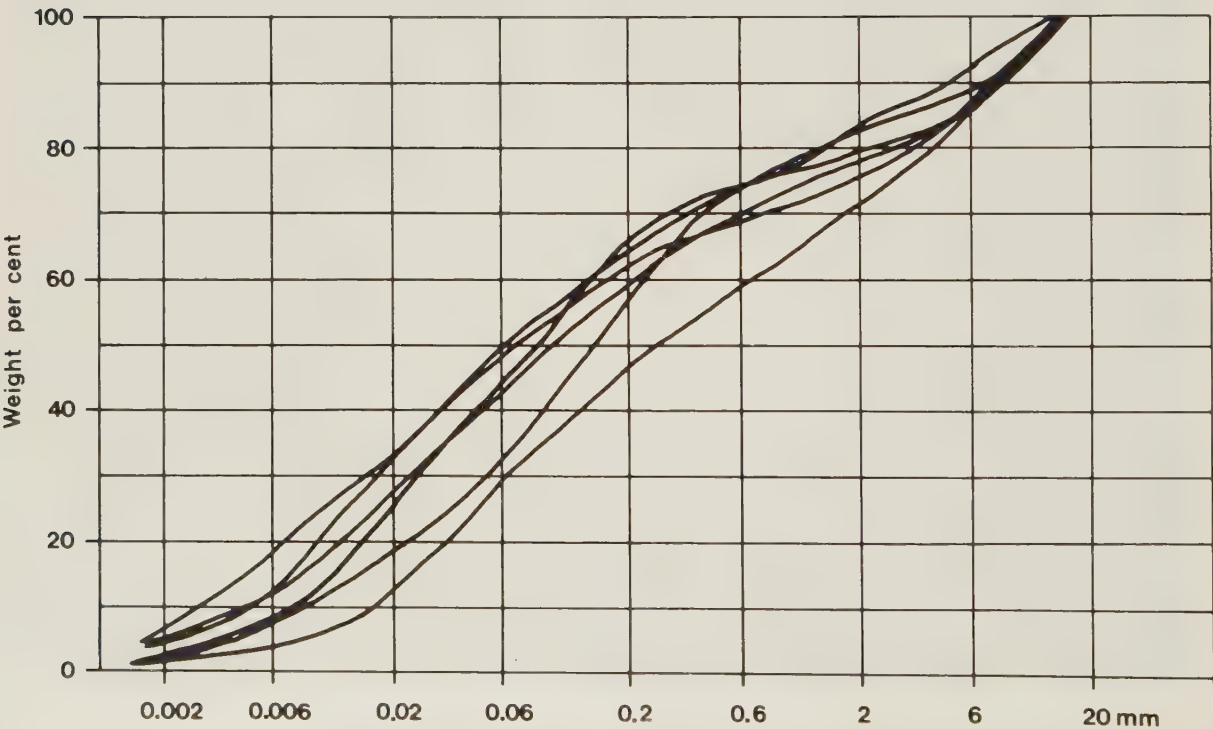


Fig. 13. The grain-size distribution of material < 16 mm in some till samples collected in the Forsmark area.



Fig. 14. A cutting wall at the initial point of the recirculation tunnel of Unit 3 showing a fine-grained till with an extremely high degree of compaction. The marks of the dipper teeth at the excavation of the till indicate the high degree of compaction of the material. Photograph by Göran Hansson/N.

characteristic feature is the concentration of the thickest layers of till to the lowest level of the bedrock which results in a levelling of the local topography. Thus, this morphological effect is a contributory cause of the flatness of the area. Next to the till, peat deposits are the most common soil type. The thickness of the peat deposits varies considerably with an observed maximum of about 2 m. Shore sand and clay occur as surface soils in the low levels of the terrain. The maximum thickness of the shore sand is about 1 m; the thickness of the clay is normally 1 m, but a maximum thickness of 3 m is recorded. Sediment filling in horizontal fractures in the superficial rock mass is a very common feature at Forsmark which will be discussed below. The thickness of the soil layers on the sea bed outside the construction area is about 2–3 m and consists chiefly of a fine-grained till which is partly superposed by fine-grained sediments and mud. As on the mainland, both the till layers and the superposed soil types reach maximum thickness at low levels.

Till. Normally the till can be characterized as a sandy, silty till, but both coarser and finer grain sizes occur. The grain-size distributions of some till samples are shown in Fig. 13, which gives an idea of the composition and range of variation of the till at Forsmark. In some parts of the area the till

shows a very high degree of compaction with a normal frequency of boulders, with some being 1 m³ in size. Otherwise the boulder frequency in the till varies from negligible to high. The till surface is to a great extent wave-washed with the result that shore till is found in several places. The wave-washed bed is normally less than 1 m thick.

During the geological explorations four trial pits were investigated in the area of Unit 3 (Hector 1975). A sandy, silty till predominates and in one pit the till is superposed by a clay bed roughly 0.5 m thick. The rock surface in all four pits was found at a depth of about 3 m below the ground surface. Approximately 400 m to the east of Unit 3, three trial pits were excavated to a depth of 5 m (Hector 1972). The upper part invariably consists of a 0.5-m-thick layer of wave-washed gravelly, sandy till and in one pit wave-washed till superposes fine-grained sediments of a silty, sandy composition with a high degree of compaction which in turn are resting on a very hard silty clay. The sediment beds are about 2 m thick and underlain by a hard clayey, silty till, which seems to indicate the presence of double moraine. At the site of the screen house of Unit 3, a blue-grey till appears. The till has a high compaction and is fine-grained with a low frequency of boulders and stones. The thickness of the till reaches a maximum of nearly 4 m. This type of till was also found in a depression of the rock surface at the bridge abutment on the eastern side of the in-



Fig. 15. The fine-grained composition of the till at the initial point of the recirculation tunnel of Unit 3. Photograph by Göran Hansson/N.

let channel. Figure 14 shows a section of a cutting wall at the area of the initial point of the recirculation tunnel of Unit 3 (cf. Fig. 4) and Fig. 15 shows an example of the fine-grained composition of the till. Because of the high degree of compaction blasting was necessary for the excavation of the till shown in Fig. 14. In this context, it may also be mentioned, that the seismic investigations made during the geophysical explorations showed a seismic velocity of about 4500 m/s in this particular area, which is not a velocity for soils. Three samples of the till were taken and the content of material less than 0.063 mm was 54.2, 54 and 59.8 per cent respectively, at sampling depths of 1.5, 2 and 3 m. To the north, this till is superposed by an approximately 2-m-thick normal sandy, silty till, while to the south, the blue-grey till seems to reach the ground surface. A sample for particle orientation of the till was collected (Agrell and Björnbom 1977) a stereoprojection of which is shown in Fig. 16. The analysis in the till shows a low tendency of orientation from NNW, which is also the youngest ice movement in the area.

A number of analyses of the calcium content were made on the local till. The samples were washed through sieves before extraction in 75 % HNO₃ and in 25 % HCl for 24 hours. The concentration was then measured on a atomic-adsorption spectrophotometer. It is difficult with wash-sieving to obtain a clear idea of the amount of calcium which really has been washed out. The calcium analyses were carried out by Mr G. Borg at the Department of Quaternary Geology at Uppsala.

Analyses of the calcium content were made on the till samples M5, M6 and M7, which represent the blue-grey till

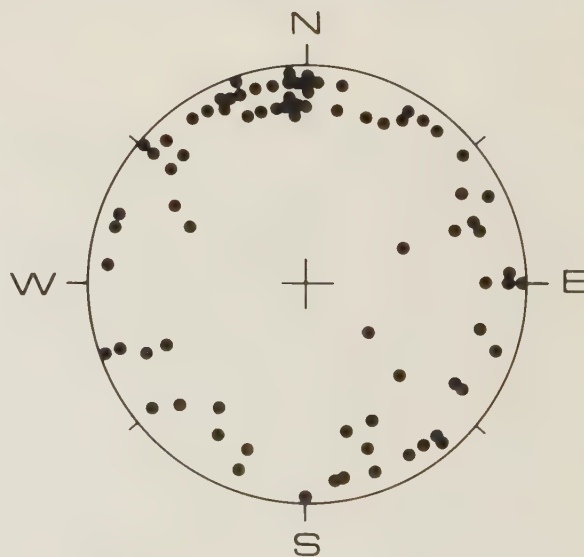


Fig. 16. Stereodigraph of particle orientation of the fine-grained till near the initial point of the recirculation tunnel of Unit 3 (after Agrell and Björnbom 1977).

from the site of the screen house of Unit 3. The result does not reveal an unduly high content of calcium. Table 1 shows the result of the calcium analyses and the highest content of calcium is 3.8 %. However, the clay fraction has

Table 1. Calcium analyses of some till samples and the content in heavy minerals and feldspar. F denotes the feldspar content. R denotes the degree of roundness. Roundness: I = angular, II = subangular, III = subrounded, IV = rounded. The sampling sites are shown in Fig. 17.

Sample no.	Type of till	Sampling depth m	Calcium content (%)			Heavy mineral (%) and feldspar (%)		
			Fractions in mm			Fractions in mm		
			0.5—0.25	0.25—0.125	0.125—0.063	0.5—0.25	0.25—0.125	0.125—0.063
M1	sandy silty	1.1	1.2	1.2	1.1	4.1	7.2	9.6
M2	sandy silty	0.8	1.0	0.9	1.0	3.9	6.2	9.2
M3	sandy silty	1.6	—	1.4	3.9	3.2	4.5	7.3
M4	sandy silty	1.3	3.5	2.3	2.0	2.6	3.6	5.9
M4 (R, F)			IV (R)	III—IV (R)	III (R)	28.7 (F)	20.9 (F)	13.5 (F)
M5	silty	2.0	2.4	—	1.7	2.0	3.1	5.2
M6	silty	3.0	3.4	2.8	2.0	2.0	3.6	3.9
M7	silty	1.5	3.8	2.1	2.0	1.9	3.7	4.5
M7 (R,F)			III (R)	II—I (R)	I (R)	33.2 (F)	27.7 (F)	22.6 (F)

not been analysed and it is possible, that the content of the clay fraction is higher than that of the analysed fractions. The calcium content of the till samples M1–M4, also shown in Table 1, is relatively low. The sampling sites of the till are marked in Fig. 17. Investigations of the calcium content in till in northern Uppland carried out by Gillberg (1967) and Ingemar and Moreborg (1976) generally give higher contents of calcium in till than are presented here.

The content of heavy minerals and feldspar in the till was determined in a number of samples. At the investigation of heavy minerals, the samples were first decalcified in 10 % HCl. After washing and drying, about 10 g were collected for gravity separation in tetrabromomethane, with a density of 2.96 g/cm³. Repeated drainage and stirring were then carried out until no more heavy minerals fell down into the separation funnel, after which the samples were washed, dried and weighed. At the feldspar analysis the light minerals were collected from the mineral separation. The samples were then fixed on glass slides and etched with fluorhydric acid for 1 min. After washing, the samples were stained with bronthymol blue. The method uses the principle that aluminium leading minerals will assume a gelatinous cover on the etching with fluohydric acid. In this case, the bronthymol blue was used to facilitate the counting of the minerals using a microscope, natural blue minerals being rare and the risk of confusion is slight. The determination of heavy minerals and feldspar was made by Mr. B. Karlsson at the Department of Quaternary Geology at Uppsala.

The result of the determination is shown in Table 1 together with the sampling sites, type of soil, average sampling depth and fractions investigated. The Table also illustrates the degree of roundness in some fractions. The degree of roundness of the particles is visually determined by using the classes of Russel and Taylor (1937:238–240), and the determinations of the degree of roundness were carried out by Mr. B. Karlsson at the Department of Quaternary Geology at Uppsala.

Sediment deposits. The low levels of the terrain contain shore gravel, shore sand and both glacial and postglacial clay but to a limited extent and at shallow depth. Järnefors (1963:40) points out that the glacial clay in the flat coastal area to the west of Öregrundsgrepen seems to be severely abraded, consisting of restratified glacial and postglacial clays. No samples of the clay were collected in the in-

vestigation area but distinct varves in the glacial clay were observed on pit walls. In general, postglacial clay occurs in connection with the peat layer.

The investigation of the harbour and channel (VBB, 1973) provided information on soil cover on the sea bed. The upper section of the sea bed near the pier (Fig. 2) consists of a layer of sandy clay about 5 m thick which superposes coarser material about 2 m in thickness. The rock surface appeared at a depth of about 7 m. In the harbour area (Fig. 2) the soil cover consists of gravelly, sandy, silty clay rich in stones and boulders. The thickness of the clay is about 2–6 m. Beneath the clay, friction material occurs which superposes the rock surface.

Ice recession. According to the description by Järnefors (1963:Pl 1), the retreat of the land-ice from the area happened between the years –650 – –600 according to De Geer’s chronology or about 7550–7500 BC according to Lundqvist (1961:85). The rate of retreat to the west of Öregrund was about 250 m/year, and to the northeast of Öregrund, the retreat of the land-ice accelerated and in the vicinity north of Gävle, the velocity of the annual ice recession was about 700 m and more (Järnefors 1963:59).

A site some 500 m south of the Forsmark church, about 15 m above sea level, is described by Järnefors (1963:40). Järnefors there demonstrates a superposed postglacial clay with an about 10 cm thick spotted zone (Järnefors 1963:58) some 4.3 m below the ground surface. The thickness of the glacial clay is about 1 m and its colour a grey-brown to black. The bottom layer consists of sand and according to Järnefors (1963:40) the varve series cover the years between –601 – –652; 52 varves.

Järnefors (1963:59), maintains that the glacial striae of northern Uppland and the Gävle area are in full agreement with the assumed direction of the ice movement based on investigations of varve chronology. Frödin (1956) presented a comprehensive survey of glacial striae from Uppland, dividing the data into three groups, each of which represents one direction, namely N45°W, N45°W–N10°E, N–S to NE.

Due to the construction works with, in some cases, incomplete cleaning of the rock surface and also to mechanical damage of the uncovered rock surface no glacial striae could be discerned in the area of the three units. However, observations were made on a rock outcrop about 400 m north-east of Unit 3 and also on some

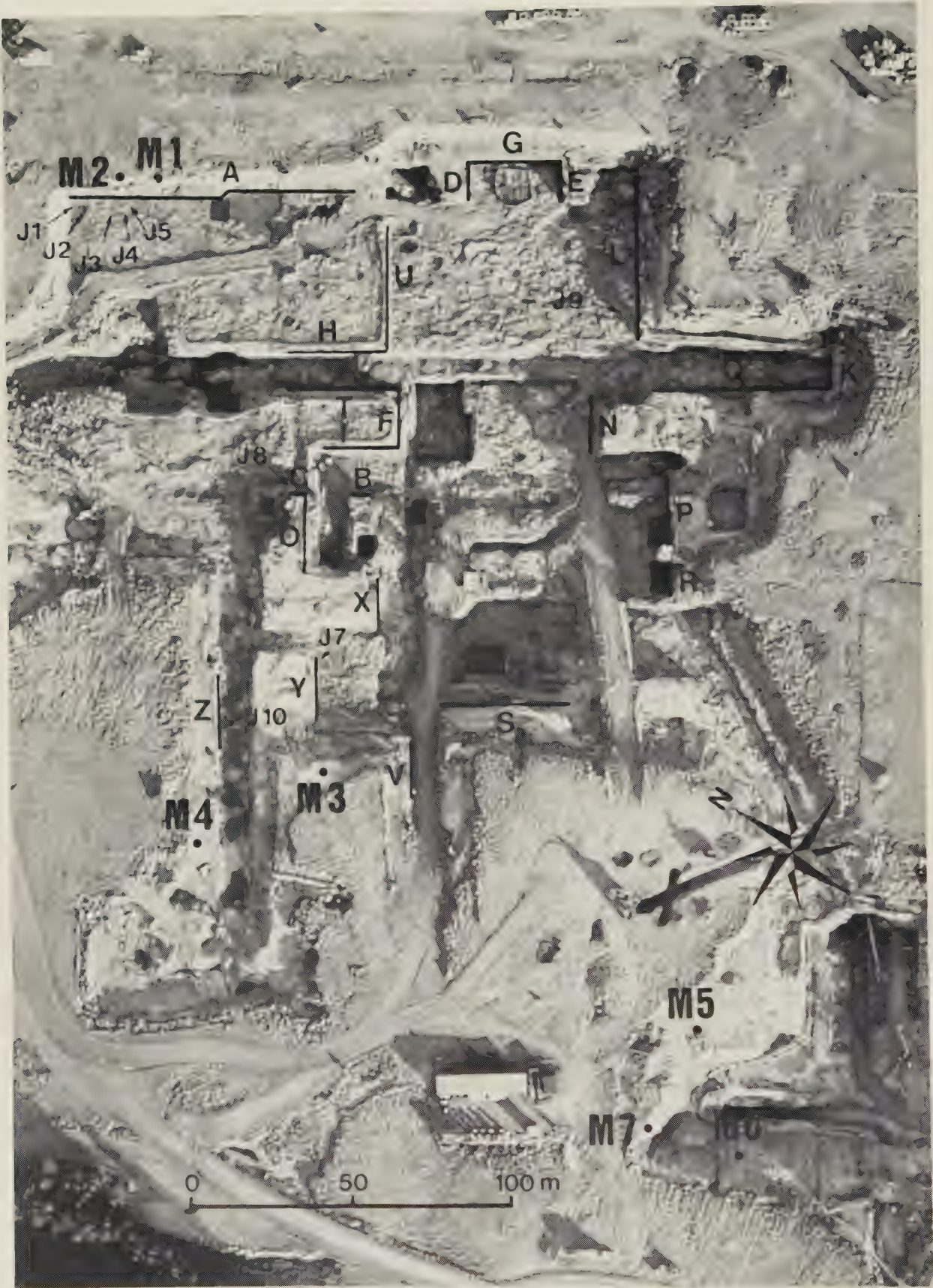


Fig. 17. The investigation area at Unit 3 showing the shaft walls (A–Z), and the sampling sites of till and sediment filling (M1–M7, J1–J10). Photograph by Göran Hansson/N.

islands in the biotest lake. The most common direction is N–S, but directions of N40°W, N20°W, and N10°E were measured as well. In all, 27 glacial striae were measured and these new measurements support the data mentioned above.

The annual uplift in the Forsmark area is about 6 mm, judging by data from the second high precision levelling along Line 40 carried out during 1951–1967 (RAK 1974:43–45).

Fracture behaviour of the superficial rock mass

In general, a rock mass may be described as an accumulation of rock units divided by a great number of geological discontinuities which intersect the rock mass in different direction of strike and dip. For example, Duncan (1969:3) defines the rock mass as traversed by fractures in the form of open joints, open bedding planes, open planes of cleavage and schistosity, and by faults and these fractures sometimes split the rock mass into blocks or units of rock material. In effect, the rock mass can often be visualised as composed of blocks of rock material, the juxtaposition of which is dictated by the fractures existing within the rock mass. Müller (1974:17) regards the rock mass as an accumulation of rock elements which are bound by the discontinuities, stating that it is not a loose disorderly heap such as we meet in a slope of debris but a strictly ordered one and, as a rule, the rock mass is a mass broken through and through due to overloading during tectonic movement occurring during and after the period of orogenetic process. In the terminology of ISRM (1975:4), the rock mass denotes simply rock as it exists in situ, including its structural discontinuities. In this paper, the rock or rock material is visualized after Broili (1974:36) as matrix of the solid phase which builds up the rock system. Discontinuity according to ISRM terminology (1977:2) is the general term for any mechanical discontinuity in a rock mass. It is therefore the collective designation of all types of joints, bedding planes, contacts and faults, a summary also made by Müller (1974:17).

According to ISRM terminology (1975:11) a joint is a break of geological origin in the continuity of a body of rock occurring either singly, or more frequently in a set or system, but not attended by a visible movement parallel to the surface of discontinuity. A fault is defined as a fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture. The displacement may be a few cm or many km. Fracture is the general term for any mechanical discontinuity in the rock; thus it is the collective term for joints, faults and cracks etc. and a fissure is a gapped fracture. The term crack denotes a small fracture; i.e. small with respect to the scale of the feature in which it occurs.

In the literature, there has been and still is confusion concerning the terms joint, fault, fracture, fissure and crack, as discussed by e.g. Price (1966:110–113), Fecker (1978:111–113), I. Larsson (1970:419–420, 1971:788–789) and Liljeqvist (1970:107, 1971:239). In this paper fracture is used as a collective term for joints, fissures, faults etc. while joint denotes fractures forming a set or a system; i.e. a joint set or a joint system. No genetic aspects are thereby taken into account, but the terminology should be considered purely descriptive. When

referring to work executed by other authors, their terminology is quoted.

All the fractures recorded at Forsmark have a length of at least 1 m, and are described as continuous or discontinuous. Here a fracture is defined as continuous when it is discernable along the whole surface of the shaft wall which means that both ends of the fracture disappear from the wall face and thereby has a continuity of 100 %. When one or both ends are visible on the wall face, the fracture is judged discontinuous.

The mechanical behaviour of a rock mass is primarily dependent on the stress situation, the rock type, the depth below bedrock surface, the mechanical and the hydraulic properties of the fractures. In order to comprehend the fracturing of the rock mass and the individual properties of the fractures, a detailed investigation must be performed with regard to all existing fractures. First and foremost, the horizontal fracturing and such specific properties as the filling material in horizontal fractures are studied in this work. However, it is necessary to scrutinize also other fractures in the rock mass with regard to these same properties, in order to perceive the position of the horizontal fractures and their status in the rock mass. Fracturing and the properties of a specific joint set can only be explained if it is studied as part of the whole.

The general occurrence of fractures and their properties are illustrated by the results of a geological survey carried out in the excavated shafts of Unit 3 (A. Carlsson and T. Olsson, 1980). This geological survey was intended to define and deduce fracture characteristics of the gneiss granitic rock mass within the Forsmark area.

Investigations were made on shaft walls running in the directions of N54°E and N36°W; the walls have orthogonally directions. Each of the investigated shaft walls in the area of Unit 3 is shown in Fig. 17. The total length of the investigated walls running N54°E is about 270 m, with a total area of approximately 950 m², while the walls representing the direction of N36°W have a total area of about 1100 m² and a total length of 285 m. This means that the investigated shaft walls are uniformly distributed. The mean height of the walls is 3.5 m (N54°E) and 4.3 m (N36°W) respectively. In all, 568 fractures were measured with regard to a number of characteristic properties given in Fig. 18. The following parameters are here used to describe the fractures of the gneiss granitic rock mass:

- orientation
- filling
- aperture
- spacing
- roughness

All the fractures were characterized in terms of orientation, filling, aperture and spacing. However, measurements of orientation of some horizontal and subhorizontal fractures proved impossible owing to a limited screen angle. Yet a statistically significant number of horizontal and subhorizontal fractures were measured, allowing a clear idea of their orientation in the area. As regards the roughness of the fracture surfaces, it is not possible to measure all the fractures because some fractures simply do not offer a sufficient surface.

The method to be used for an investigation of fractures and their properties depends on various factors. But it must be possible on the basis of recorded fracture data, to

FIELD DATA RECORD SHEET

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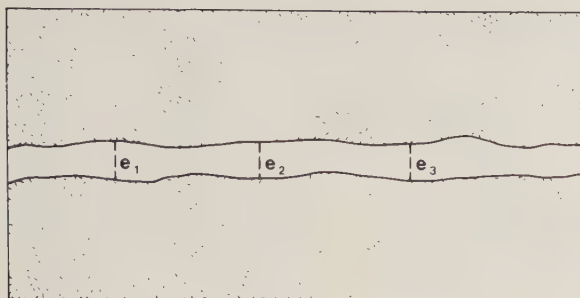


Fig. 19. The principle of measuring fracture apertures.

arrive at more or less valid approximations of the fracture characteristics of the rock mass. Such an investigation provides the basis of judgements of the properties and also of a general description of the rock mass. The investigation method used in this work is based on the philosophy of the cumulative sums method of analysis described by Piteau and Russel (1971) and Piteau (1973). According to Piteau (1973:13), the cumulative sums method of analysis is sequential in that the dip or strike values of the fractures are considered in the order in which they are derived along the survey line. The chief advantages of this technique are according to Piteau (1973:13), that it is possible to detect general changes in the fracture orientation data, to determine where changes in fracture orientation take place in the rock mass, and to determine a reliable estimate of the mean orientation of the fractures at any point along the surveyed pit face. Moreover, it is possible to predict the average orientation of a particular joint set, or group of joints, in other parts of the mass where information is not available.

The limited investigation area permitted a systematic study of all the fractures with a length of 1 m or more, hence no sampling method was needed beyond the exclusion of fractures less than 1 m in length. A field data record sheet was devised for the field work and the arrangement of the data is shown in Fig. 18. A similar type of check list for systematic structural surveys is for example given in Louis (1974:359). After the field work, the fractures and their individual parameters were combined into a number of joint sets which are reported below in connection with orientation. The data were then coded and stored on magnetic tape. The fracture parameters were stored in the order of their appearance on the field data record sheet and each parameter can be used as a search-concept. A computer of type HP with plotter was used for the calculations and six data files were utilized.

Joint surveys, rock mass classifications, statistical analyses of fractures for various purposes have been treated by several authors, for example Bray (1967), Király (1970), Bieniawski (1973), Wickham and Tiedemann (1974), Barton, Lien and Lunde (1974), Fourmaintraux (1975), Laubsher and Taylor (1976). Statistical analysis of geological data is extensively described by Krumbein and Graybill (1965).

Definitions and measuring fracture parameters

Only parameters used in this work will be described and attention will not be paid to other parameters shown on the field data record sheet in Fig. 18. The definitions are mainly in agreement with those given in ISRM (1975, 1977).

The spatial orientation of a fracture is defined by its strike and dip. Strike is the direction or azimuth of a horizontal line in the plane of an inclined stratum, fracture, joint, fault, cleavage plane or other planar feature within a rock mass. Dip is the angle at which a stratum or other planar is inclined from the horizontal. The measurements of the fracture orientation used a compass with clinometer with a scale divided into 400 parts, which was then converted into the old 360° system. The scale of the clinometer was 0–90°.

Filling is the material generally occupying the space between fracture surfaces, in joints, faults, and other rock discontinuities. The filling material may be sand, silt, clay, breccia, gouge, various natural cementing agents or alteration products of the adjacent rock. The filling material was identified in the field and no laboratory investigation was performed apart from that concerning the sediment fillings. In the case of the sediment material, both disturbed and undisturbed samples were collected for laboratory analysis. As regards other filling materials, an identification of primary and secondary mineral content was made in the field.

The term aperture denotes the perpendicular distance between adjacent rock walls of a fracture separated by air or water, or when other filling material is wholly or partly washed-out. Here, if the intervening space is filled with material rather than air or water, and the filling is intact, the perpendicular distance between adjacent rock walls is termed fracture width. In measuring small fracture apertures, a feeler gauge was applied and in the case of larger fracture apertures, the distances between their surfaces were measured with a measuring tape. The principle of measuring fracture apertures or the width of the filling material is illustrated in Fig. 19; the obtained value of the aperture or the width is a mean value based on a number of measurements of the aperture or the width along the fracture.

Spacing is here defined as the perpendicular distance between individual fractures in a single joint set. From the mean spacing of the individual fractures, it is then possible to calculate the joint frequency of each joint set. The distance between the fractures of one joint set was measured with the help of a ranging pole about 1 m above the shaft bottom with an angle of approximately 90° between the pole and the fractures. This procedure was followed when measuring both vertical and horizontal fractures with one exception, the distance in the case of horizontal fractures is measured downwards from the crest of the wall. The mutual distance between subvertical or subhorizontal fractures was measured independent of the angle between the pole and the fracture and therefore, according to ISRM (1977:37) the spacing(s) was corrected as follows for directional bias according to the direction of strike and dip

Fig. 18. Field Data Record Sheet showing the parameters recorded at the joint survey made in the area of Unit 3. Columns 1–6 represent shaft wall data, and 7–21 fracture data. 1. Wall number. 2. Height. 3. Length. 4. Direction. 5. Dip angle. 6. Rock type. 7. Number of fracture. 8. Distance from starting point. 9. Strike. 10. Dip. 11. Length. 12. Continuity. 13. Type of continuity. 14. Type of filling. 15. Sample of filling. 16. Aperture. 17. Spacing. 18. Roughness profile. 19. Wall strength. 20. Intensity of water flow. 21. Angle of friction.

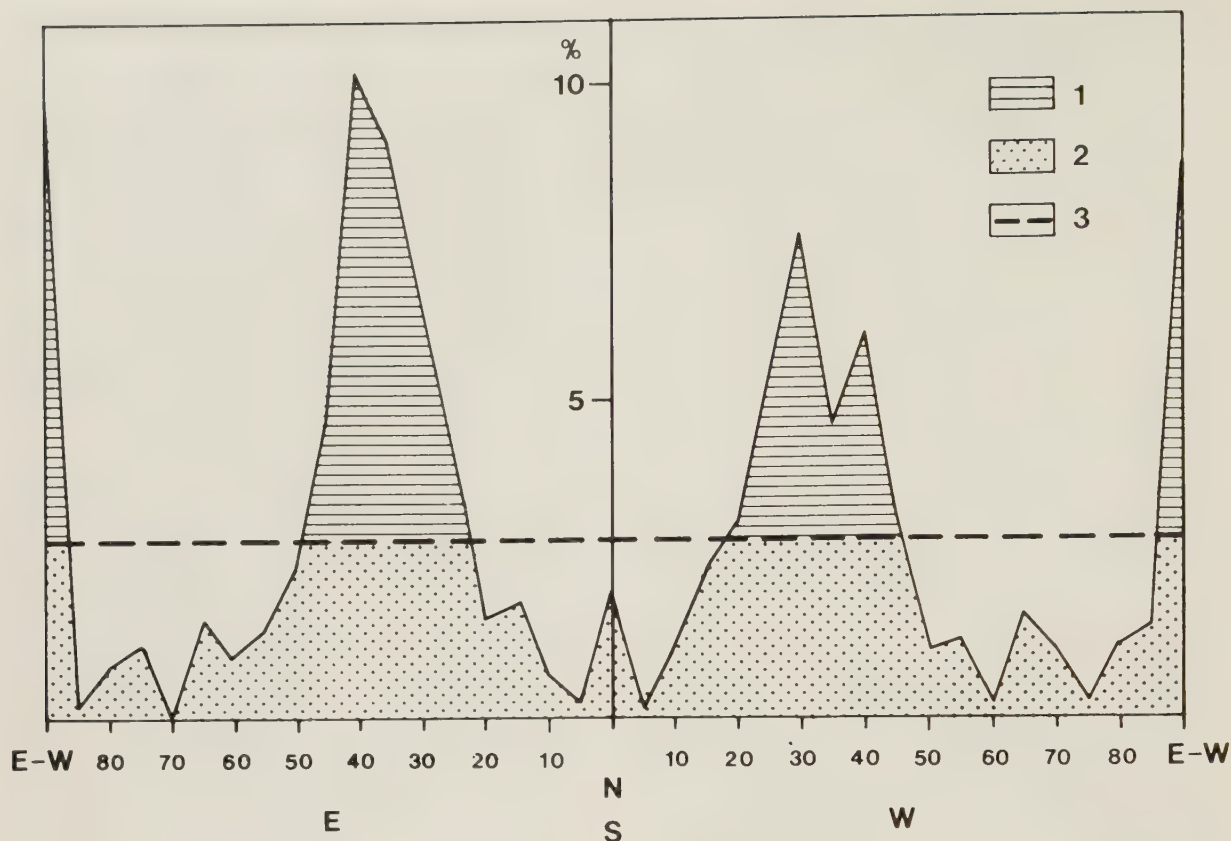


Fig. 20. Graph of boundaries of each joint set, based on data recorded in the area of Unit 3. 1. Most frequent directions of joint sets. 2. Frequency below randomly distributed fractures. 3. Distribution at which all fractures are randomly distributed.

relative to the sampling direction:

$$s = d_m \cdot \sin(\alpha) \cdot \sin(\beta)$$

where s = spacing

d_m = modal spacing

α = strike

β = dip

The nature of fracture surfaces, here termed roughness, is the inherent surface roughness and waviness relative to the mean plane of discontinuity. Both roughness and waviness contribute to the shear strength. Large scale waviness may also alter the dip locally. The roughness profiles of the fracture surfaces was recorded with help of a profile form 130 mm in length. The roughness profiles were sampled by linear profiles along three directions; one profile parallel to the strike direction of the fracture, one perpendicular to the strike, and one deviating 45° from the strike. The profile form was depressed and the depression drawn on millimetre paper. The depression line then provides the basis for calculating the mean value of the roughness or unevenness of the fracture surface which is indicated by the maximum amplitude of the waviness. Methods of measuring roughness, and its importance for rock mechanics are presented in detail by e.g. Barton (1971), Barton and Choubey (1977), Rengers (1970), Fecker and Rengers (1971) and Fecker (1978).

Treatment of fracture parameters and results

Orientation. In order to obtain the frequency of the various strike directions of the fractures of the rock mass in the

area, the direction of each fracture was related to a grouping in cells with an interval of 5° . The percentage distribution of fractures within each cell was calculated, and a graph plotted. In order to visualize the range of variation within the joint sets, the true frequencies of direction were compared with a hypothetical case, where all the fractures are randomly distributed. The purpose of this comparison was made to reduce to a minimum the occurrence of close-directional random joints. In the hypothetical case, all the directions have the same frequency.

The terms joint set, joint system and random joints are often used in this work, and the reader is referred to Terzaghi (1965) for clear and logical definitions. Terzaghi (1965:288) makes the obvious and true comment, that many of the joints observed at a single outcrop are approximately parallel to one or several planes, those joints which have approximately the same orientation constitute a set of joints, while the regional joint system consists of these sets characteristic of the region. Joints belonging to any of these sets may be described as systematic joints. Following Terzaghi (1965:288), joints which belong to no recognized set will be designated random joints, and a locality in which only random joints are present may be said to exhibit a random joint pattern. However, it is an open question if random joints truly exist. The limits of the joint sets are here defined as the directions where the frequency of occurrent fractures exceeds the case of merely random joints. This classification is intended to promote a primary sorting of the total fractures measured in the area. Furthermore the same sorting was used for computer processing of the different parameters.

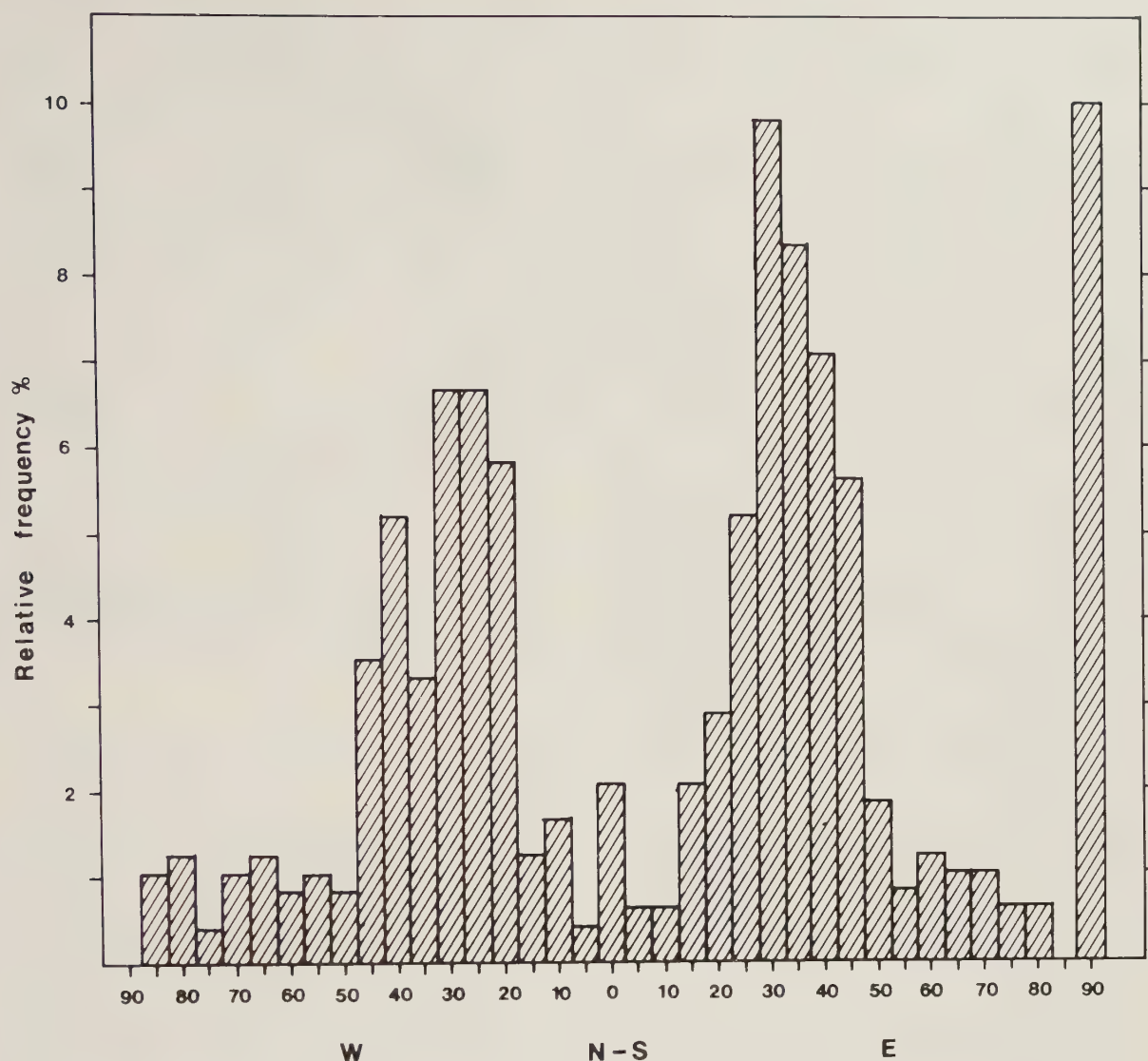


Fig. 21. Histogram of the distribution of strike directions of all the vertical and subvertical fractures measured in the area of Unit 3.

The result of the measurements of the orientation is shown by a stereographic projection (Fig. 22), and by histograms (Fig. 21). The stereographic projection illustrates the strike and dip of all fractures in addition to a number of horizontal fractures with an immensurable orientation. The strike measurements of all the vertical and subvertical fractures recorded on the shaft walls at Unit 3 are given in histograms. The dip values of each individual set are similarity presented.

The limits of these joint sets are graphically defined in Fig. 20 while the limit values of each set, together with the range of variation, are shown in Table 2. Table 2 also includes the horizontal set and random joints. The number and the percentage of joint sets 1, 2 and 3 respectively and of random joints are assigned to the total share of the vertical and subvertical fractures. The horizontal and subhorizontal fractures Joint Set 4, was excluded from this calculation. In all, 69 horizontal fractures were recorded

Table 2. Sets of joints in the area of Unit 3 with characteristic directions and frequencies. The table represents all the recorded fractures in the area of Unit 3.

Sets of joints	Main direction	Cell boundaries	Width of interval	Number	Frequency in per cent	Intensity
1	E-W	N86°W-N86°E	8°	48	9.6	1.2
2	NW-SE	N18°W-N46°W	28°	148	29.7	1.1
3	NE-SW	N22°E-N49°E	27°	183	36.7	1.4
4				69		
Random joints			117°	120	24.0	0.2

on the shaft walls at Unit 3 with respect to the parameters given in the field data record sheet, but the strike direction could only be determined on 25 horizontal and sub-horizontal fractures.

The distribution of all the measured fractures on the shaft walls at Unit 3 which dip vertically or subvertically is illustrated in Fig. 21. As the figure shows, there are three distinct maxima of directions, namely E–W, NW–SE, and NE–SW, but the distinction of the three sets varies considerably. The stereographic projection in Fig. 22 shows the measurements of the strike and the dip with the exception of 44 horizontal and subhorizontal fractures. Measurements of horizontal and subhorizontal fractures performed on other shaft walls in the area, however, agree with the result of the measurements presented in Fig. 22; i.e. a main strike direction of approximately N25°W.

Figure 23 illustrates the distribution of the dip measurements for each joint set while Table 3 gives the maximum, mean and median values of the dip together with the standard deviation. According to Piteau (1973:9), the average maximum error is generally speaking estimated as $\pm 10^\circ$ for strike measurements and around $\pm 5^\circ$ for dip measurements, inclination of the structure being most important. Piteau (1973:3) points out that for flat-lying structures of the order of 5° to 10° , where the horizontal line of projection is extremely limited, the strike may be as much as $\pm 20^\circ$ in error. Hence, obvious difficulties arose in measuring the strike directions of the horizontal and subhorizontal fractures on the wall faces, considering that the median value of the dip of these fractures is about 2.5° .

Terzaghi (1965:298) gives some prerequisites for adequate joint surveys and emphasizes that in the limited area of a construction site the number of outcrops, the distribution of their blind spots, and the uniformity of distribution of outcrop area among the various orientations may be insufficient to provide a fair sample of joint orientations unless corrections are applied. However, in the case of the survey at Unit 3, the arrangement of the investigated walls allows observation of all the fracture directions due to the orthogonal distributed directions of the shaft walls. Fractures with a strike direction parallel to the direction of the walls running N54°E will be observed on the shaft wall faces running N36°W. As stated above, the total lengths of the walls in the two directions are 270 m and 285 m respectively representing a total area of 950 m² and 1100 m². It is thus possible to assert, that there is a uniform distribution of the directions of the walls, and the recorded fractures can be seen as a sample of good approximation of their orientation.

In the Forsmark case, however, horizontal and subhorizontal fractures will be underrepresented in comparison with vertical fractures by reason of the relation between the length and depth of the individual shaft walls. Fractures striking in the direction of the rock foliation may be underrepresented, for in the case of blasted shafts it may be difficult to distinguish whether or not a fracture developed as a result of the blasting. This probably does not apply to the present survey because most of the vertical fractures in the area show mineral coatings on their fracture surfaces, indicating that they are old structures, and therefore, not caused by blasting. With the exception of the direction of E–W, the gneiss granite shows a joint pattern with a strike direction of NW–SE which fairly well agrees with the foliation, and an orientation maximum

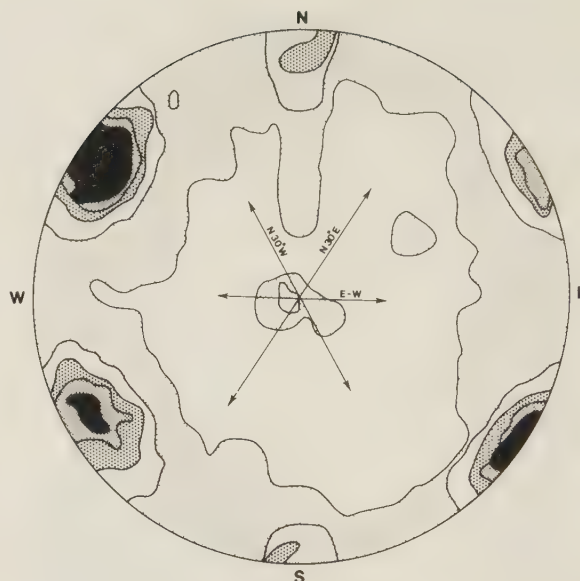


Fig. 22. Fractures in the rock mass of Unit 3. Stereographic projection of the poles of fractures. Lower hemisphere, Schmidt's net. Contour density 3–6–9–12–15 %. Arrows indicate main directions of sets of joints.

perpendicular to the foliation which means a direction of NE–SW.

In the Forsmark area there is a definite difference between the two main rock types as regards the joint pattern. This is because the foliation of the paragneiss is significant for fracture feasibility, while the fracturing in the gneiss granite is less dependent thereon.

As regards the dip values, with the exception of the horizontal set, there is no noticeable difference between each joint set and random joints. The median value of the vertical sets is about 85° and of the horizontal set about 2.5° . Yet, the standard deviation of the dip in Joint Set 1 is about twice as high as for the other sets and random joints.

Filling. The types of filling material found in the fractures and their distribution within each joint set and random joints calculated as a percentage are shown in Fig. 24. The result is based on data from all the recorded fractures on the shaft wall faces at Unit 3. Thus Joint Set 1 has the highest frequency of unfilled fractures, the frequency being rather uniformly distributed in the other sets and random joints. Chlorite predominates in all the fractures, but in the horizontal set most of the fracture surfaces are partly coated with chlorite, which means that mineral coatings appear as patches. An example of that is given in Fig. 25. This applies only to the horizontal and subhorizontal fractures, while the whole fracture surface area of the vertical fractures is coated with chlorite, as seen in Fig. 26.

Calcite and laumontite consistently accompany the chlorite filling. Laumontite does not occur as a single coating in the fractures of the horizontal set or with the chlorite alone, but is found in the fractures of the other sets and random joints.

Another characteristic feature as regards the horizontal and subhorizontal fractures is the sediment filling. Sedi-

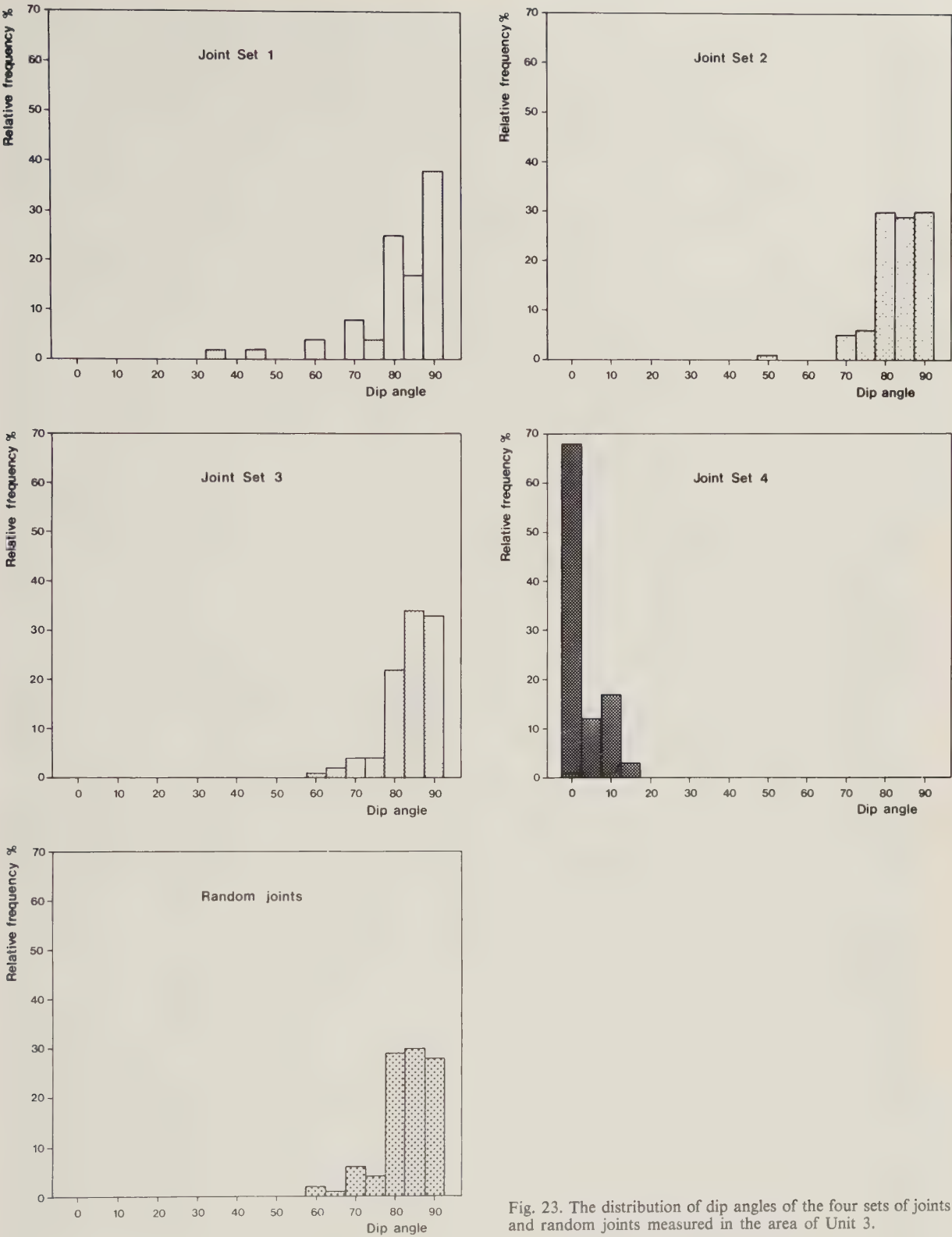


Fig. 23. The distribution of dip angles of the four sets of joints and random joints measured in the area of Unit 3.

ment filling was found in about 83 % of the fractures belonging to the horizontal set recorded at Unit 3. This type of filling occurs only in a few fractures in Joint Set 2 and in random joints. When vertical fractures contain sediment filling they are intersected by horizontal fractures also with sediment filling. The sediment filling in the area will be described and discussed separately later.

Aperture. The results of the physical measurements of fracture apertures greater than 0.1 mm are illustrated in Fig. 27, in which the apertures are related to each set and to random joints. The number of fractures with apertures less than 0.1 mm within each of the sets is given in Table 4. For the purpose of classification, vertical fractures with apertures larger than 10 mm were excluded, but here to,

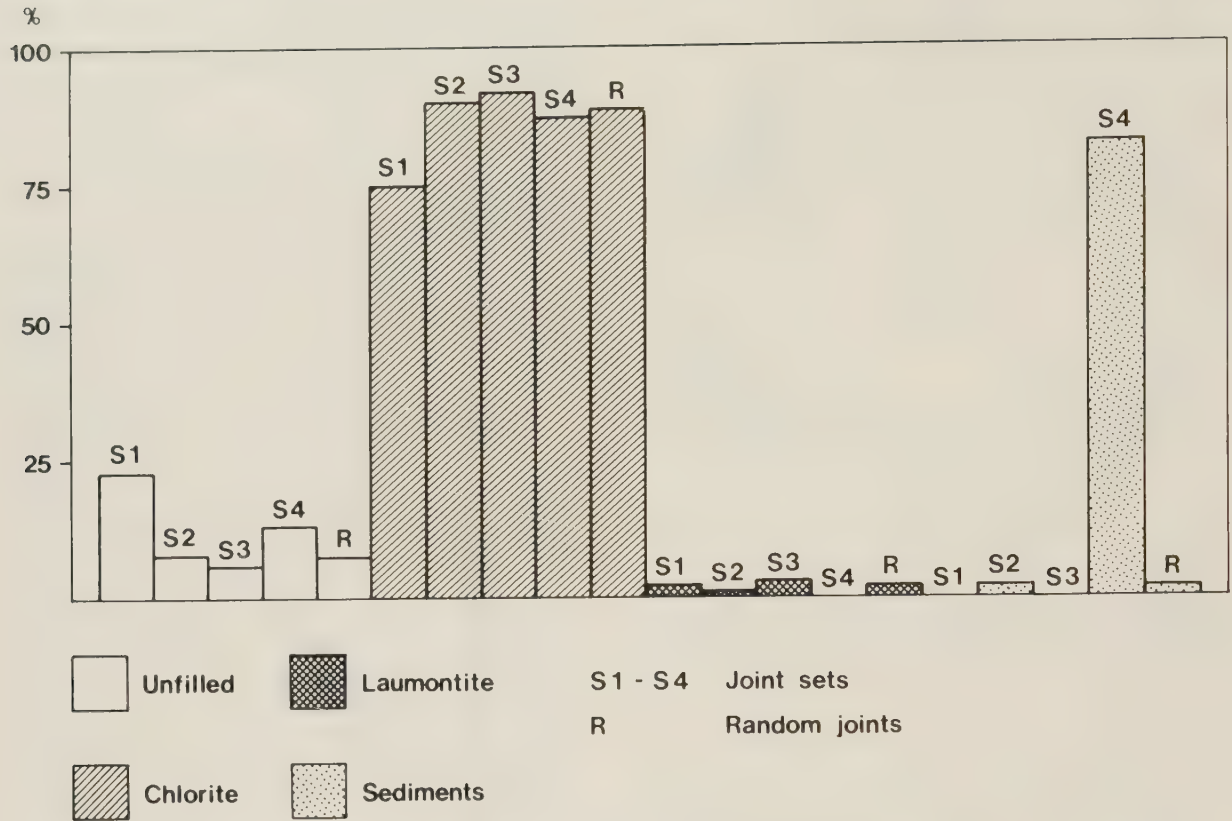


Fig. 24. Types of filling material and their distribution within each set of joints and random joints calculated as a percentage.

the number of apertures exceeding 10 mm is given in Table 4 which indicates that few aperture values are larger. The same situation prevails in the horizontal set, but here fractures with apertures larger than 200 mm were excluded whereupon only one fracture had a larger aperture, namely 220 mm. Table 4 gives the basic statistics of the apertures, the values being derived from the total number of fractures.

As implied by Fig. 27 and Table 4, there is a considerable difference between the aperture of the horizontal and the other sets. The obtained mean value is decidedly higher than the median value because the former is governed by the physical method of measuring whereby fractures with apertures less than 0.1 mm are immensurable. The median value is therefore a more accurate measure of the fracture apertures.

Qualitative terms are often used to describe fracture apertures and according to ISRM (1977:89), the fractures of the sets 1, 2 and 3 and random joints may thereby be designated as very tight features while the fractures of the horizontal set may be described as very wide fractures and open fractures. These definitions are based on the respective median values. Nevertheless, it must be emphasized that the values of the apertures measured by the physical method must be accepted with caution. For the gas pressure at blasting may cause expansion of the fractures. Mechanical damage inflicted by loaders may also affect the fracture apertures. In this context, it can also be said, that during blasting new fractures may develop along planes of weakness in the rock. This process may be triggered by the sudden heavy vibration accompanying

detonation due to the expansion, causing deformation of the rock mass. Therefore, in connection with a joint survey carried out in blasted shafts it is essential carefully to examine fractures with the blasting in mind, so that fractures so caused will be disregarded. Moreover, measurements of fracture apertures on rock outcrops do not yield a relevant result either by reason of the weathering effect.

Because of the difficulties of arriving at significant values of fracture apertures, and of obtaining information on the apertures at greater depths, hydraulic tests were used, there being a well-defined relation between the fracture aperture and the water-bearing capacity of the fractures (cf. A. Carlsson and T. Olsson 1978b).

The results of the geological explorations for the foundations of the power plant were used to calculate the apertures of the fractures on a hydraulic basis. In this context, the results derived from 29 diamond-drilled boreholes in which water pressure tests were performed. The depths of the individual boreholes vary from 19 m down to 130 m below rock surface, and both vertical boreholes and boreholes with an inclination of 45° were drilled. The cores were examined with regard to petrography and fracture frequency (Larsson and Moberg 1975) and the values of hydraulic conductivity calculated according to a method described in A. Carlsson and T. Olsson (1977b, 1977c, 1979a, and 1980b).

The value of the fracture aperture thereby obtained represents the mean of the apertures of all fractures within the test section. Consequently, the mean value refers neither to the individual fractures nor to the variation of



Fig. 25. A horizontal fracture surface showing patches of chlorite coatings. The dark area represents chlorite, the grey the non-coated fracture surface, and the light areas are sediments. Photograph by Göran Hansson/N.



Fig. 26. A vertical fracture surface on the northern shaft wall of the surge basin at Unit 3 showing continuous mineral coating. Photograph by Göran Hansson/N.

the apertures and conductivity, but represents imaginary fractures with a continuous, constant fracture aperture. The hydraulic conductivity of the rock mass will not

change when the true fractures are replaced by these imaginary fractures.
Statistical treatment of the result from the 317 test sec-

tions produced a range of variation of aperture of 3 μ m to 1100 μ m with a mean value of 71 μ m. The mean value, the median value, and the range of variation are shown in Table 5, and the distribution of the calculated fracture apertures in Fig. 28. Thus the mean is consequently lower than the median value, possibly due to the fact that a relevant value of the hydraulic conductivity is not obtained for tight rock masses, but the rock mass has a conductivity value which corresponds to the lower test limit of the water pressure test. In this case, the true value of the hydraulic conductivity is less than, or equal to, the value of the hydraulic conductivity of this test limit. By this method, the value of the fracture aperture obtained is also to be regarded as a maximum, the true value consequently being less. This means that the calculation of the mean value yields too a high a value for the aperture and the median value therefore represents a more accurate value of the fracture aperture. The result of the calculation shows that the apertures of the fractures are very small, but in view of the fact that the calculations give a constant, continuous value, the true apertures of the fractures will locally be considerable larger.

Spacing. The results of the measurements of the fracture spacing of the individual joint sets are shown in Fig. 29 and in Table 6. No distinction was made with respect to different continuity types, but the result is based on both continuous and discontinuous fractures. When comparing with the qualitative terms of spacing given in for example ISRM (1977:38) and the median spacing of each set, the spacing of Joint Set 4 may be designated as medium spacing (0.3–1.0 m) while the spacing of the other sets and random joints lies within the range of 1–3 m which, according to the qualitative description can be described as wide.

The maximum values for the spacing of individual sets and random joints are similar, except for the horizontal set

which has a maximum spacing value of 1.7 m. This is consistent with the intensity of horizontal fractures in the superficial rock mass. The lowest mean and median values are to be found in the horizontal set which also has the lowest value for the standard deviation, namely 0.4. The fact that horizontal fractures present small spacing in the uppermost rock mass is confirmed by other investigations made in the area such as diamond-core drillings. The occurrence of horizontal and subhorizontal fractures as a function of depth will be discussed later.

Roughness. The calculations of the readings of the surface roughness of the fractures are given in Table 7. In all, 282 readings were made on both coated and non-coated fracture surfaces. As stated above, the roughness profiles were sampled by linear profiles along three directions on the fracture surfaces, i.e. one profile was taken parallel to the strike direction of the fracture, one at right angles, and one with a 45° deviation. The values of the roughness presented in Table 7 for each of the sets and random joints are mean values of the profile directions, relevant to coated and non-coated fracture surfaces. The Table includes the mean value of each set and random joints based on all the measurements.

A fracture surface may be described as an irregular curved surface which itself consists of a number of elements with different properties. The fracture surface can therefore be divided into a number of units and its profile of a surface is distinguished by a more or less pronounced waviness. The variation of the waviness is therefore a consequence of the viewing scale. Here, attention will only be paid to a small scale of waviness representing the 130-mm-long profile used for the measurements. There are difficulties in assessing this small scale of waviness mainly because the waviness is slight in comparison with the accuracy of measurement. The maximum and minimum

Table 3. Results of all measurements of dip within each set of joints in the area of Unit 3.

Sets of joints	Maximum	Minimum	Dip angle β° Mean	Median	Standard deviation
1	90	35	81	84	11.6
2	90	50	83	84	5.9
3	90	60	84	85	5.7
4	15	0	2.4	2.5	4.1
Random joints	90	60	83	84	6.3

Table 4. Result of all measurements of fracture aperture in the area of Unit 3.

Sets of joints	Maximum	Minimum	Aperture Mean	Median	Standard deviation	Number of apertures in percent less than greater than	
	mm	mm	mm	mm		0.1 mm	10 mm
1	40	0.1	2.0	<0.1	6.3	47.9	8.3
2	30	0.1	1.2	<0.1	3.1	39.2	5.4
3	60	0.1	1.2	<0.1	6.5	55.7	2.7
4	220	1.0	25.3	14	33.8	0	
Random joints	40	0.1	2.3	<0.1	7.1	49.2	8.3

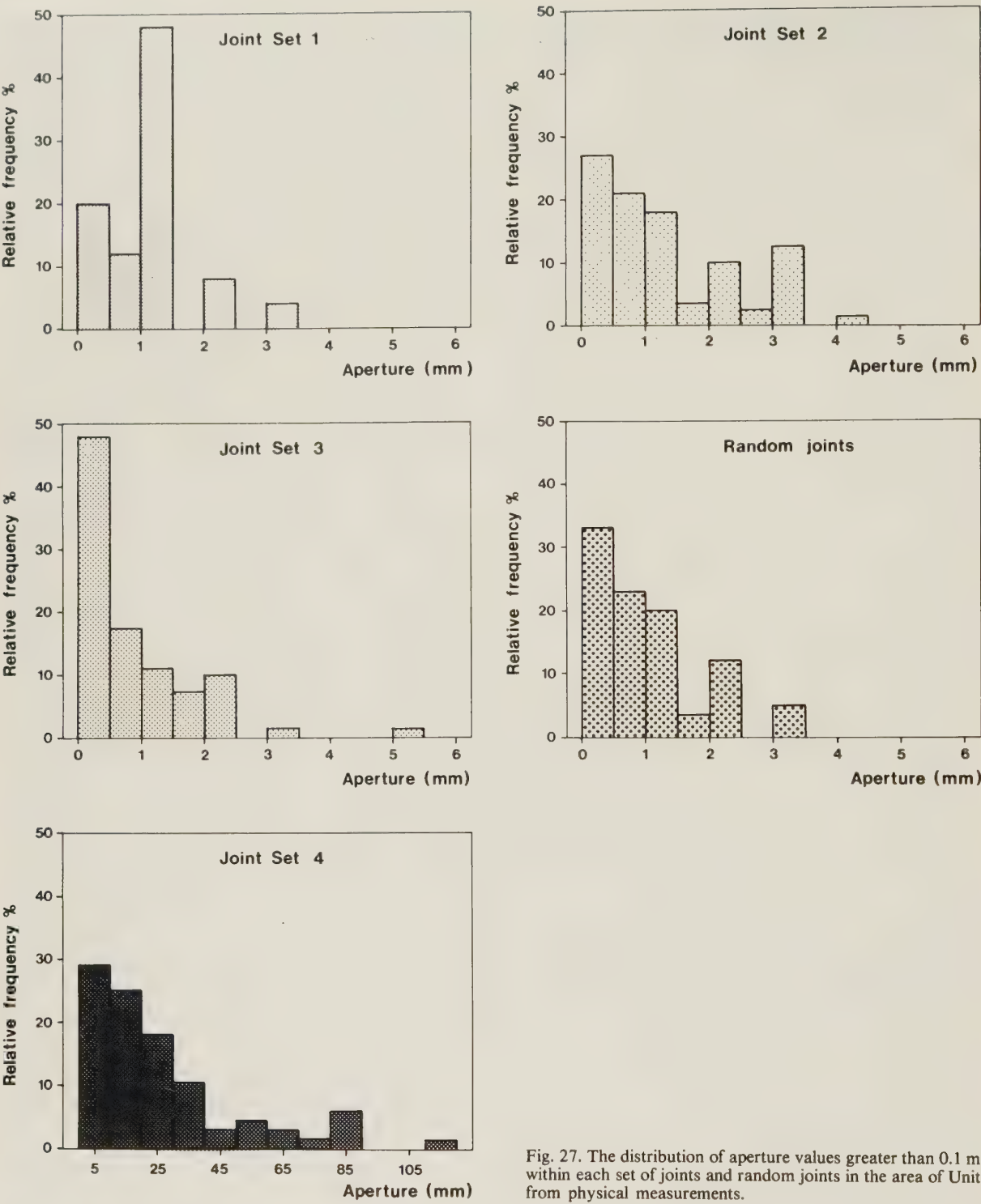


Fig. 27. The distribution of aperture values greater than 0.1 mm within each set of joints and random joints in the area of Unit 3 from physical measurements.

Table 5. Values by means of hydraulic tests calculated on fracture apertures at Forsmark.

Fracture apertures μm		Mean	Standard deviation	Median	$e_{75}-e_{25}$
Maximum	Minimum				
1100	3	71	82	47	63

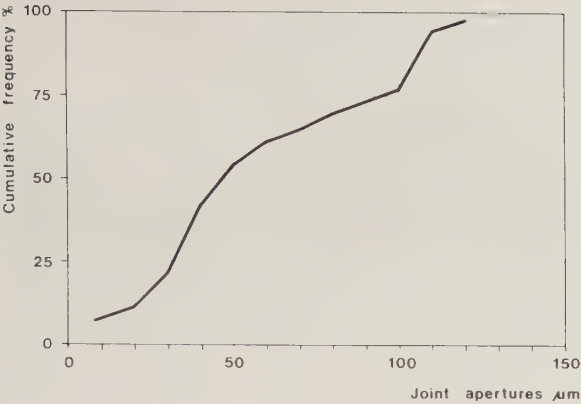


Fig. 28. Distribution of fracture aperture values in the gneiss granite in the Forsmark area obtained from hydraulic tests in drill-holes (A. Carlsson and T. Olsson 1978b:130).

amplitudes within the range of measurement constitute the basis of the determination, being defined by a linear through the terminal points of the profile. The small scale waviness is defined as the sum of points of intersection on the straight line which connects the maximum and minimum value. In Fig. 30 the method of determining the small scale of waviness and the roughness value of the fracture surface can be expressed as:

$$\zeta = \frac{a}{d/2}n$$

where a = the amplitude (mm)
d = the length of the wave (mm)
n = point of intersection

The values of the roughness presented in Table 7 are slightly higher as regards the horizontal as compared with the other sets and random joints. The roughness values of the non-coated are consistently higher than those of the coated fracture surfaces. A larger number of roughness

measurements should probably have been carried out to allow for more accurate measure of the difference in roughness between coated and non-coated fractures as well as between the different sets.

The occurrence of horizontal and subhorizontal fractures in the Forsmark area

A characteristic feature of the gneiss granitic rock mass within the construction area of Forsmark Power Station is the occurrence of horizontal and subhorizontal fractures intersecting the steep dipping structure of the gneiss granite. These fractures occur throughout construction area composed of gneiss granite but are not to be found within the paragneiss area. Moreover, the horizontal fractures are concentrated to the upper part of the rock mass; they are present at greater depths but to a lesser extent. The occurrence deep below the rock surface was proved by investigations in the submarine-tunnel, situated approximately 60 m below the rock surface, and by a great number of rock drillings made in the area. In the superficial rock mass, horizontal fractures are to a great extent filled with sediment material which will be described in detail later. On the whole, horizontal and subhorizontal fractures containing sediment filling were observed on the wall faces in all excavated shafts in the gneiss granitic part of the Forsmark area.

The characteristics of the horizontal and subhorizontal fractures in each of the investigated shafts in the area are not appreciably different as regards the individual fracture parameters, such as orientation, lengths, spacing, apertures, filling material and surface roughness. Moreover, there is no noticeable difference concerning e.g. the relation between horizontal fractures and topographical features, rock foliation and other discontinuities in the rock mass. However, differences as regards the above conditions and parameters may exist locally in a single shaft as well as between different shafts. In one shaft, for example, the superficial rock mass may show a difference in fracture

Table 6. Result of all measurements of fracture spacing in the area of Unit 3.

Sets of joints	Maximum m	Minimum m	Spacing Mean m	Median m	Standard deviation
1	8.5	0.1	2.4	1.3	2.4
2	8.7	0.05	1.7	1.2	1.8
3	10.0	0.05	1.8	1.0	2.2
4	1.7	0.05	0.6	0.7	0.4
Random joints	9.3	0.1	2.4	1.9	2.1

Table 7. Roughness values representing the four sets of joints and random joints.

Sets of joints	Non-coated	Roughness values Mineral-coated	Total mean	Number of surfaces measured
1	0.30	0.24	0.27	60
2	0.32	0.22	0.27	60
3	0.24	0.19	0.22	51
4	0.33	0.29	0.31	54
Random joints	0.30	0.27	0.29	57

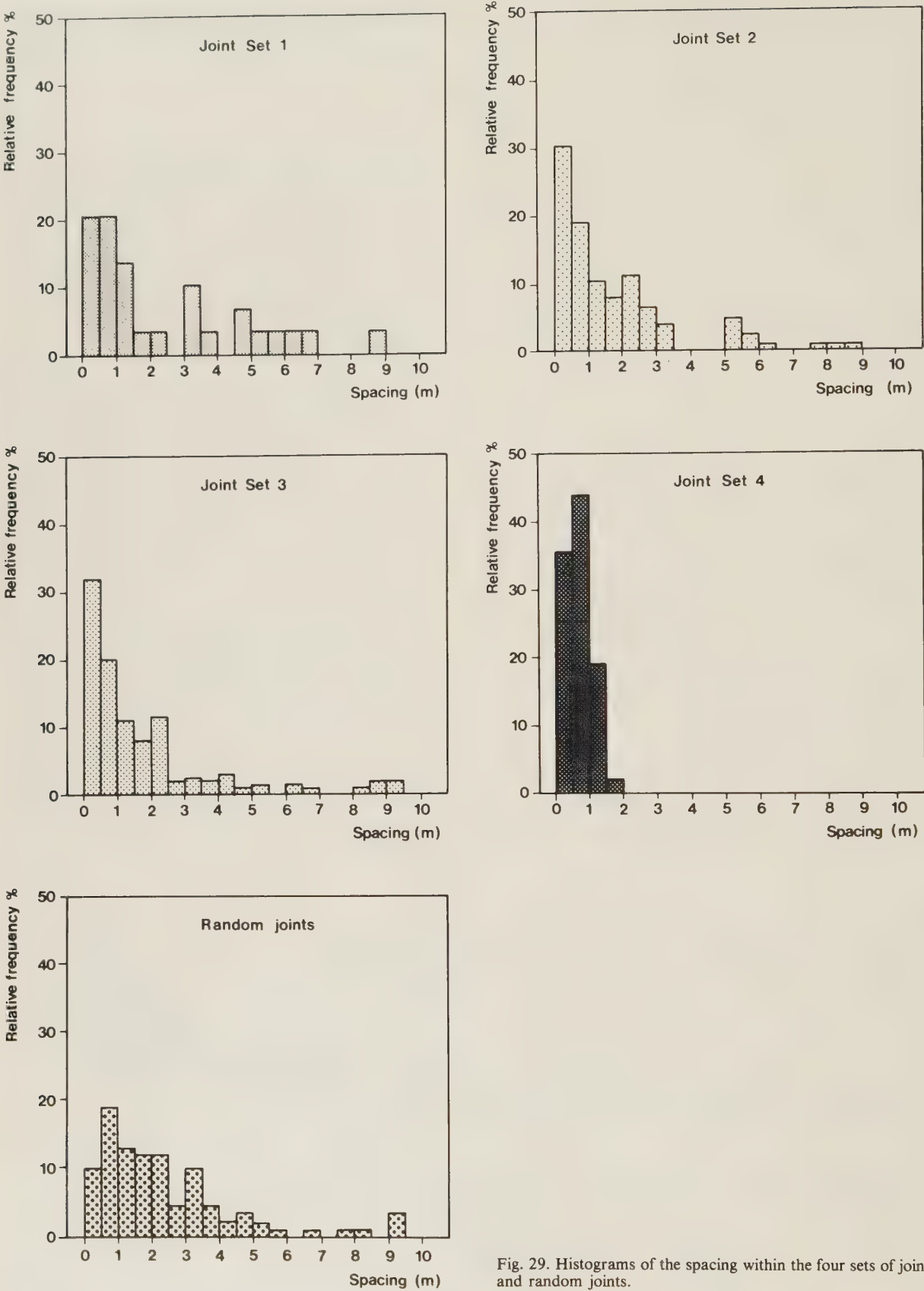


Fig. 29. Histograms of the spacing within the four sets of joints and random joints.

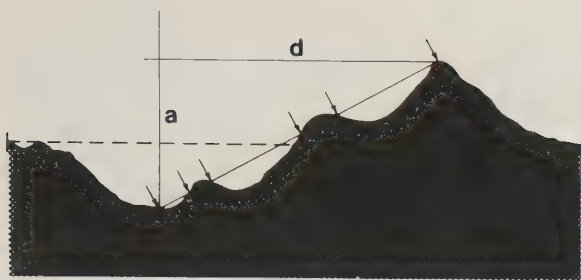


Fig. 30. A roughness profile and the principle of determining the minor waviness. a. The amplitude. d. The half length of wave. n. Points of intersection.

intensity and degree of crushing. Locally along a shaft wall the rock mass may be strongly influenced by intense fracturing and the fractures may there contain large quantities of crushed rock and thick sediment filling (Fig. 31). At a distance of 20 m from the heavily fractured area, the rock mass may be almost devoid of fractures and crushing with the exception of a normal occurrence of both horizontal and vertical fractures. In such a section, the horizontal fractures generally show a smaller aperture with or without sediment filling and a rare occurrence of rock fragments in the fractures (Fig. 32).

The occurrence of horizontal and subhorizontal fractures in the area was also documented by a great number of drill-holes. These drillings coupled with observations in the excavated shafts confirmed not only that horizontal and subhorizontal fractures occur throughout the gneiss granitic part of the construction area, but also that horizontal and subhorizontal fractures filled with sediment materials are present as well.

However fractures filled with sediment are confined to the superficial bedrock, and has been observed to a maximum depth of about 13 m below the original rock surface. Generally speaking, the horizontal fractures are concentrated in the upper part of the bedrock, as was verified by rock drillings and observations in various tunnels excavated in the area. The headrace tunnel of Unit 3 is one instance (Fig. 3), being covered by a rock mass in which horizontal and subhorizontal fractures with and without filling material of sediments occur. In the tunnel horizontal and subhorizontal fractures are seen on the skew back but no sediment filling could be discovered. The rock cover of the tunnel is about 14 m and the distance between the skew back and the floor of the tunnel is about 6 m. Figure 33 shows the initial point of the headrace tunnel and the horizontal and subhorizontal fractures in the superposed rock mass can be seen.

The western shaft wall of the surge basin shown in Fig. 34 may be said to represent the most typical behaviour of the horizontal fractures, and the occurrence of sediment filling in the Forsmark area. The uppermost part of the rock mass down to a depth of roughly 5 m below the rock surface is characterized by horizontal and subhorizontal fractures and fracture apertures varying from a few mm to 200 mm. These fractures usually contain sediment filling and rock fragments. Below the 5-m-level there is an increase in spacing and a drastic decrease in aperture of the horizontal and subhorizontal fractures. Normally, the apertures are less than 0.1 mm and no sediment filling or

rock fragments whatever are found. However, crushed rock is naturally present in different types of zones of weakness at greater depths below the rock surface. The occurrence of horizontal and subhorizontal fractures in relation to depth below rock surface will be discussed later.

The horizontal set is composed of a number of flat fractures which have created a characteristic feature of the superficial rock mass at Forsmark. In the uppermost part of the rock mass, the fractures show a small spacing and commonly intersect other structures in the rock mass such as vertical and subvertical fractures belonging to the other joint sets, individual crush zones, fracture zones, dikes and fragments of other rock types found in the gneiss granite such as greenstones and pegmatites. By intersecting other fractures in the rock mass and by their regularity, the horizontal fractures produce to a blocky structure. Due to the orientation of the steeply dipping fractures, the shape of the blocks will be irregular, but regular or square shapes occur when the two orthogonal directions predominate.

The relation between horizontal and subhorizontal fractures and other features of the rock mass

As appears from Fig. 35, dikes of amphibolitic greenstones and pegmatite are intersected by horizontal fractures. There is a pronounced gneissosity in the gneiss granite at Forsmark with a mean foliation running N36°W and dipping about 85° to the north-east, although variations in direction occur. Elements of greenstones and pegmatites in the gneiss granitic rock mass are frequent and both the greenstones and the pegmatites are generally found as dikes parallel to the rock foliation but also as isolated bodies while the pegmatite also appears as larger massifs or intrusions. The horizontal and subhorizontal fractures intersect these occurrences of greenstones and pegmatites throughout the investigation area.

A number of fracture zones are to be found on the investigated shaft wall faces all of which are intersected by horizontal and subhorizontal fractures. A fracture zone intersected by horizontal fractures is shown in Fig. 36. The vertical zone is roughly 2 m wide and has a strike direction of N40°E. The vertical fractures occurring in the zone are filled mainly with chlorite and calcite, but surface coatings of laumontite are also seen. With one exception the horizontal fractures which intersect the fracture zone are filled with sediment. The apertures of the horizontal fractures vary from 0.5 mm to approximately 50 mm.

As described in the previous chapter, the rock mass may be defined by four joint sets and random joints. Joint Set 1 has a strike direction of roughly E–W (N86°W–N86°E), Joint Set 2 includes fractures with a strike direction of N18°W–N46°W, and Joint Set 3 has a strike direction almost perpendicular to the foregoing set, N22°E–N49°E. Joint Set 4 represents the horizontal and subhorizontal fractures with a strike tendency similar to that of the Joint Set 2. The Joint Sets 1, 2, 3 and random joints represent the vertical sets with a mean value for the dip of 85°.

In general, the three vertical sets and random joints are intersected by the horizontal and subhorizontal fractures. Figure 37 shows a wall face with horizontal fractures with and without sediment filling. The vertical fracture zone on the left hand side of the picture has a north-eastern strike



Fig. 31. A section of the eastern shaft wall of the inlet channel. The rock mass is heavily fractured and the horizontal and subhorizontal fractures contain thick sediment fillings and large quantities of crushed rock. Photograph by Göran Hansson/N.

and is intersected by the horizontal fractures. In addition to those in the fracture zone (Joint Set 3), vertical fractures belonging to Joint Set 2 and random joints occur on the wall face which are also intersected by the horizontal fractures. The horizontal fracture indicated in the figure has a filling of sediment with a maximum thickness of approximately 100 mm. Consequently, it is evident that horizontal fractures intersect the gneiss granitic rock mass independent of other fractures, fracture zones, and the existing dikes and intrusions of greenstones and pegmatites. Cameron (1945:196), describing structural features of granites, says *inter alia* fractures which approach the horizontal are seen to cut all the other types of joints. Reporting on characteristic features of sheet structure, Jahns (1943:78) points out that this is wholly independent of all primary structures in the rock, and individual fractures commonly transect e.g. small pegmatite, aplite and granite dikes. Another comment on the relation between sheeting joints and other structures of the rock from Twidale (1973:170) mentions that sheeting joints cut across other structures in the bedrock such as orthogonal joints, cleavage, rift and grain and flow structures. This state of affairs has attracted the attention of many authors.

Consideration of individual properties of the superficial horizontal fractures and other fractures in the uppermost rock mass will describe that these are widely divergent. For example, there is an obvious difference in fracture aperture between the individual joint sets. The mean value of the Joint Sets 1, 2 and 3 and of random joints lies in the range of 1.2–2.3 mm, while the horizontal set shows a mean

aperture of 25.3 mm. As mentioned earlier in the paper, the median value is probably a more significant value of the fracture apertures due to the physical measuring method; for the vertical sets and random joints it is less than 0.1 mm and for the horizontal set about 14 mm. In the area of Unit 3, the maximum value of the fracture aperture of the horizontal set is 220 mm, while the maximum values of the other sets and random joints vary between 30–60 mm. In the storage basin for industrial water (Fig. 38), a maximum value of aperture of about 500 mm was measured for one horizontal fracture. This fracture also contained sediment filling occupying the full width of the aperture. The maximum value of fracture aperture which was measured in the Forsmark area as a whole amounts to approximately 820 mm, and was observed on the eastern shaft wall face in the inlet channel. Figure 39 shows the horizontal fracture with the aperture of 820 mm, and an underlying fracture with an aperture of about 350 mm. These fractures are filled with sediment, the width of the filling being approximately the same as for the fracture apertures. Consequently, there is a marked difference in the degree of opening between the horizontal and subhorizontal and the vertical fractures in the uppermost rock mass. Moreover, there is a marked difference in aperture regarding the horizontal and subhorizontal fractures at a rock level of about 5 m below the original rock surface (cf. Fig. 34). Below this level open horizontal fractures are rare, save in fracture or crush zones. Studies of the hydraulic conductivity of the rock mass in the Forsmark area and its relation to depth (cf. A. Carlsson and T. Olsson 1977b), imply



Fig. 32. A section of the eastern shaft wall of the inlet channel about 20 m from that shown in Fig. 31. There is a distinct difference in fracture behaviour in the rock mass. Photograph by Göran Hansson/N.

that it decreases with increasing depth. The decrease of the hydraulic conductivity with depth is also an indication of a decrease of aperture with depth. According to A. Carlsson and T. Olsson (1977b:77) the equation for the dependence of the hydraulic conductivity on depth down to about 75 m below rock surface is as follows:

$$k = 10^{-(0.04D + 5.6)}$$

where k = hydraulic conductivity (m/s)

D = depth below rock surface (m)

and its correlation coefficient 0.62. The equation is based on water pressure tests at altogether 30 drillholes of which 15 are vertical and 15 are drilled at angle. Measurements were made at 324 levels in all.

As regards the filling material in the fractures, the horizontal and subhorizontal fractures hold an exceptional position in relation to other fractures in the rock mass, since about 82 % of the fractures of the horizontal set are filled with sediment. In the event, apart from the horizontal set, only Joint Set 2 and random joints contain filling material of sediment and then to a very limited extent, while the fractures belong to the other sets show no trace of sediment filling. Chlorite is the predominant filling material in the vertical fractures, and appears also as mineral coatings in the horizontal and subhorizontal fractures. However, it is a very common feature of superficial horizontal fractures that mineral coatings occur in patches on the fracture surfaces. Investigations in the area surrounding Unit 3, also revealed that some vertical fractures there

contain sediment filling, but according to the above, the few such fractures, are in contact with horizontal fractures filled with sediment. This means that the horizontal fractures in the superficial gneiss granitic rock mass differ considerably from the vertical fractures as regards the filling.

The results of the measurements of the spacing reveal a difference between the sets and random joints. The median value of the horizontal set is about 0.7 m, which represents the lowest value of spacing. The corresponding values for the Joint Sets 1, 2 and 3 and the random joints are 1.3 m, 1.2 m, 1.0 m, and 1.9 m respectively. There is also a considerable difference in maximum spacing if a comparison is being made between the different sets, and the maximum spacing of the horizontal set is only 1.7 to be compared with 8.5–10 for the other sets and random joints. However, this state of affairs is consistent with the relation between depths and lengths of the shaft walls.

In order to calculate the dependence of the horizontal and subhorizontal fractures on depth, results from a vertical core drilling was used, DBT3. When this study was made, the bore hole had been drilled down to a depth of 100 m below the rock surface. When the result were processed, a subdivision into 5-m-sections was made in order to discover the depth dependence of the horizontal and subhorizontal fractures. Fractures which intersect the drill-hole at an angle of 20° or less to the horizontal plane were classified as horizontal and subhorizontal fractures. Fig. 40 illustrates the mean spacing of each section, plotted against the vertical component of the drilling depth.



Fig. 33. A view of the initial point of the headrace tunnel at Unit 3 showing horizontal and subhorizontal fractures in the rock mass covering the tunnel. The dark areas on the shaft wall above the tunnel point are shotcrete. Photograph by Göran Hansson/N.

Except for the regression line, a number of functions have been tested in order to work out the amount of the dependence of spacing on depth by using the least square method. The equation which best satisfied the measured result is as follows:

$$S = \frac{D}{0.99D + 8.55}$$

where S = the mean spacing (m)

D = the depth below rock surface(m)

In order to assess the fit of the line to the measured values, the correlation coefficient r^2 was ascertained. This factor has a value between 0 and 1, where the value 1 indicates that the line fits the series of points completely. The correlation coefficient is 0.5 for the above equation.

The graphic representation in Fig. 40 indicates a decrease in spacing between the levels 0–5 m, 5–10 m, 45–50 m, 85–90 m, 90–95 m, and 95–100 m. The zones with a high frequency of horizontal and subhorizontal fractures can be regarded as fracture zones surrounded by rock masses of a more intact rock character. The dependence on depth of the spacing in the fractured zones can be determined from the following equation:

$$S_z = \frac{D}{1.99D + 5.92}$$

where S_z = the spacing in fracture zones (m)

D = the depth below rock surface (m)

The correlation coefficient in this case is 0.78. The cor-

responding equation of the spacing of the intervening rock masses runs as follows:

$$S_R = \frac{D}{0.65D + 9.81}$$

where S_R = the fracture spacing in the more intact rock (m)

D = the depth below rock surface (m)

and its correlation coefficient is 0.88.

Figure 41 shows the spacing in the horizontal and subhorizontal fracture zones and the spacing of the intervening rock masses in relation to the vertical component of the drill-hole. On the basis of the results in Fig. 40, a rough outline of the occurrence of horizontal fracture zones at depth is shown in Fig. 42. The extension in length is thereby hypothetical.

If only the upper 25-m of bedrock are considered, the best correlation appears to exist within this interval. The correlation coefficient here is 0.92. In order to obtain more data for determining the depth dependence of the horizontal and subhorizontal fractures within the superficial bedrock, results from 10 core-drillings in the area of Unit 3 were used. Each of the bore holes was drilled to an approximately depth of 30 m. In the processing of the drilling results, angles of inclination in the range of 0–10° were recorded for the rock levels 0–10 m, 10–20 m, and 20–30 m. The mean fracture frequency of the corresponding sections proved to be 3.7, 3.4, and 2.0 fractures per meter



Fig. 34. The western wall of the surge basin of Units 1 and 2. The superficial rock mass down to a depth of about 5 m has a well developed joint pattern composed chiefly of horizontal and subhorizontal fractures filled with sediment and rock fragments. The total height of the shaft wall is about 20 m. Photograph by Göran Hansson/N.

respectively. The results from the drill-hole DBT3 and from the 10 drillholes drilled to an approximate depth of 30 m show a manifest increase in spacing of horizontal and subhorizontal fractures down to a depth of 30 m below the rock surface. However, conclusions concerning the degree of spacing at depths below 30 m are more difficult to make on the basis of one drill-hole only.

Spacing of sheet fractures at depth has been investigated by several authors and Dale (1923:32) for example has found, that the sheets increase in thickness more or less gradually downward, while Jahns (1943:73) states, that with increasing depth the sheets tend to become progressively thicker, more nearly horizontal, and less irregular. The increase of the sheet thickness from the surface downwards was also demonstrated by Dahl (1968:154). Correlations of thicknesses of sheets and depths with tops of sheets in granite are given by Johnson (1970:365) who demonstrates an increase in sheet thickness with an increase on depth.

If the data obtained at Forsmark are compared with those quoted by Jahns (1943:73) and Johnson (1970:365), it will be seen, that the correlation in the latter case is better than that reached at Forsmark if the superficial rock mass is excluded. However, it is crucial that the observations made in the Forsmark area be based upon drillings, so that the spacing of the horizontal and subhorizontal fractures is assessed independently of the lengths of the fractures. An analysis of sheet thickness was also made by Johnson

(1970:386–390) who defines his premise in an attempt to explain the observed variations by saying that part of the strain energy induced by unloading of the granite is transformed into surface energy and plastic work along newly formed sheet fractures, as the granite is brought toward the ground surface. According to this premise, there is a critical strain energy, above which sheet fractures form. Johnson suggests the following expression for the thickness of sheets:

$$t' = \frac{1}{[1-(z/D_0)]^2}$$

where z = the depth below rock surface

D_0 = the critical depth for sheeting

Thus the thickness of the sheets should be minimal near the ground surface and increase with depth, verging on infinity as D_0 is approached. At Forsmark there is a tendency to increased spacing with increased depth but as Twidale (1973:169) points out, in a general way the thickness of the sheets increases with depth though in detail there are many exceptions

The lengths of horizontal and subhorizontal fractures observed on the wall faces of the different shafts in the investigation area range from a few cm up to a recorded maximum of approximately 170 m. This maximum length of a horizontal fracture was measured in the inlet channel. The term fracture length is here regarded as equal to the actual length of a fracture observed on a wall face, and not



Fig. 35. A section of the western shaft wall of the inlet channel showing a horizontal fracture intersecting dikes of amphibolitic greenstones and pegmatites. No horizontal displacement of the sheets can be observed. Photograph by Göran Hansson/N.

related to strike or dip continuity. The horizontal and subhorizontal fractures occur as both continuous and discontinuous fractures and discontinuous fractures include fractures with either one or both ends visible on the wall face. No difference in fracture lengths in relation to the orientation of the shaft walls was observed. On the wall faces of the inlet channel, the horizontal and subhorizontal fractures are larger than in other shafts, but this is because the walls in the inlet channel are the longest in the area.

The most persistent horizontal and subhorizontal fractures tend to occur in the uppermost part of the rock mass, down to a depth of about 3 m below the original rock surface. However, due to the limited height of the shaft walls, it is difficult to form a true opinion of the persistence of the fractures in relation to depth below rock surface. In the discharge tunnel of Units 1 and 2, horizontal and subhorizontal fractures approximately 75 m long were observed at a depth of about 60 m below rock surface, and in the discharge tunnel of Unit 3 situated about 20 m below the rock surface, fracture lengths up to about 50 m were recorded. However, no systematic investigation was made of the persistence at depth of horizontal and subhorizontal fractures.

Johnson (1970:362) points out on the basis of investigations in a quarry that the sheet fractures seem to reach maximum length at a depth of about 30 m below the original ground surface, and to decrease with depth below this level. Johnson (1970:381–385) analysed relations between depth and length of sheet fractures and, for ex-

ample, that the length of sheet fractures increases very rapidly near the ground surface and at shallow depths the sheet fractures are very long.

Terminations of horizontal and subhorizontal fractures were studied on the wall faces in the excavated shafts in the area. These investigations showed that the termination of a horizontal and a subhorizontal fracture can consist of:

- the bedrock surface
- a vertical or subvertical fracture
- a horizontal or a subhorizontal fracture
- a crush zone or a fracture zone
- the rock matrix

This means that the terminations of horizontal and subhorizontal fractures vary considerably. Most of the horizontal fractures which terminate on the bedrock surface, are superficial a great number then being filled with sediment. Figure 43 shows such a fracture. Furthermore horizontal and subhorizontal fractures may terminate at the contact with a vertical or a subvertical fracture but the horizontal fractures usually cut across the vertical fractures. Figure 44 depicts a horizontal fracture terminating in a vertical fracture: It frequently happens, that the horizontal and subhorizontal fractures terminate in other horizontal fractures, as illustrated in Fig. 45. Horizontal fractures may be interrupted by a fracture zone, as shown in Fig. 36, but they generally cut across the fracture zones. Moreover on many wall faces, it was observed, that



Fig. 36. The shaft wall marked B in Fig. 17 showing a vertical fracture zone intersected by horizontal and subhorizontal fractures. The marks on the wall face were made by drilling cutters. Photograph by Göran Hansson/N.

horizontal and subhorizontal fractures may terminate in the rock matrix itself, and gradually fade and disappear, as illustrated in Fig. 46. No difference in termination of fractures could be discerned in individual shafts within the area but all these types are found in each shaft. The majority of the most superficial horizontal and subhorizontal fractures terminate at the bedrock surface while for the somewhat deeper lying fractures, termination in the rock matrix is predominant.

As mentioned earlier, the horizontal and subhorizontal fractures occur only in the gneiss granitic part of the area, and being lacking in the paragneiss. In the gneiss granite however horizontal fractures occur independent of other rock types which there appear as dikes, massifs and intrusions. Among the results of 10 core-drillings on the site of Unit 3 and in the adjacent, 1364 angles of inclination ($0-90^\circ$) were investigated. These were subdivided into fractures with an inclination to the horizontal plane of $0-10^\circ$ occurring in gneiss granite, greenstones and pegmatites. In the gneiss granite, down to a depth of about 30 m below the rock surface, about 67 % of the fractures could be classified as having an angle of inclination to the horizontal less than or equal to 10° . Approximately 62 % of the fractures occurring in pegmatites down to about the same depth below rock surface consist of fractures of this same inclination. As regards the third rock type, greenstones are not present in a statistically significant number of levels down to a depth of 10 m below rock sur-

face so that this section was excluded and the occurrence of horizontal fractures was investigated within the level of 10–30 m below rock surface. About 59 % of all the fractures intersecting the greenstones from 10 m down to a depth of 30 m below rock surface consist of fractures with an inclination less than or equal to 10° . This study shows that there is no pronounced difference as regards horizontal and subhorizontal fractures between the gneiss granite itself and the types of rock present in the gneiss granite, such as dikes, massifs and intrusions of greenstones and pegmatites.

Soen (1965:22) studied the relation between sheeting and rock types on Sermersôq, Greenland and states, that sheeting was not observed there in the schists or the gneisses with pronounced gneissose structures. The fact that sheeting is most frequent in granitic rocks is evidenced by a great number of works, e.g. Gilbert (1904), Dale (1923), Ljungner (1930), Jahns (1943), Chapman and Rioux (1958), Chapman (1958), Soen (1965), Johnson (1970) and Twidale (1973). Indeed Soen (1965:23) points out that among the granitic rocks which may show well developed sheeting porphyrite biotite granites are common, but hornblende granites, syenites, monzonites, gneissic and foliated granites too are frequently sheeted. The gneiss granite at Forsmark is attributed to the last mentioned type. However, sheeting may occur in other types of rock such as gneisses, described by Branner (1896) and in massive sandstone. Sheeting in sandstone



Fig. 37. The shaft wall marked C in Fig. 17 showing a fracture behaviour similar to Fig. 36. The filling material in most of the horizontal fractures consists of sediments with a maximum thickness of 100 mm. Photograph by Göran Hansson/N.

was reported by Bradley (1963). Soen (1965:23) mentions that when sheeting occurs in gneisses and non-granitic rocks these rocks nearly always appear in a spatial relationship between large scale sheeting and the occurrence of certain granite massifs rather than any relation between large-scale sheeting and the compositional or textural characteristics of granitic rocks.

The horizontal and subhorizontal fractures and their relation to topography

From a morphological point of view, the investigation area is very flat. Locally there are differences in level in the bedrock where also a somewhat pronounced parallelism can be observed between the bedrock surface and more or less horizontal fractures. Figure 47 gives an example of horizontal fractures parallel to the bedrock surface. Within the investigation area both the bedrock surface and the horizontal and subhorizontal fractures dip slightly to the east.

Sheet structure and its relation to topography has been discussed by various authors. Soen (1965:13), who studied sheeting and exfoliation in the granites, points out that the planes of sheeting in the granites clearly follow the glacial topographical forms of the third and most recent cycle of erosion. Chapman and Rioux (1958:118) describe sheeting and jointing in granite in Acadia National Park, Maine,

and assert that sheeting is well developed over most of the granite area investigated and, in general, it roughly conforms with the present topography, although numerous departures from parallelism occur. From investigations of more than 100 quarries in New England, Dale (1923:32) concludes that, there is a general parallelism between the sheets and the rock surface, resulting in a wavelike joint structure and surface over large areas. However, he also points out that although the sheet structure and the rock surface are generally parallel, they are not universally so. Moreover, Jahns (1943:73) describes sheet structure in granites in New England and points out, *inter alia*, that sheeting generally conforms to the topography. Twidale (1973:169) gives some characteristics of sheeting joints, maintaining that they commonly run parallel to the land surface and in valley floors or on broad crests are either rectilinear or gently arcuate and flat. Other works deal with this parallelism but also show that departures occur.

Horizontal and subhorizontal sediment-filled fractures in the Forsmark area

Horizontal and subhorizontal fractures filled with sediment material were found in all the excavated shafts within the construction area of the Forsmark Power Plant. Similar fractures and the same type of filling material were



Fig. 38. A shaft wall of the storage basin showing a continuous horizontal fracture containing filling material of sediments. The maximum thickness of the filling is about 500 mm. Photograph by Göran Hansson/N.

also observed at rock drillings during the geological and geophysical explorations of the site. Yet, with regard to filling material of sediment recorded at rock drillings, the observations must be adjudged less reliable than those made on wall faces in excavated shafts because of the risk of erosion of the sediment material. In the excavated shafts of Unit 3, a detailed survey was made of all the exposed shaft walls shortly after blasting. Horizontal and subhorizontal fractures with sediment filling were found on each. The deepest sediment-filled fracture was observed near the 7 m level, i.e. the fracture was about the same depth below the rock surface as the maximum shaft in the area of Unit 3. In the surge basin of Unit 3, a sediment-filled fracture was found 13 m below the original rock surface, and the bottom of the basin being approximately 18 m down. The surge basin of Unit 3 is the westernmost shaft of the construction area and thereby the westernmost excavated shaft in which horizontal and subhorizontal fractures containing filling material of sediments were observed. The most profound horizontal fractures with sediment filling observed at rock drillings within the area of Unit 3 were found at depths of 8 (D330), and 8.5 m (D338) below the rock surface.

On the whole horizontal and subhorizontal fractures occur in the area of Unit 2 to the same extent as at Unit 3, but no systematic survey was made of the shaft walls at Unit 2. The deepest lying sediment-filled fracture observed on the shaft walls of Unit 2 was found approximately 6 m below

the original rock surface. The author did not chart the area of Unit 1 because of the advanced construction at the time of the first field study in 1974. According to the geological and geophysical explorations of Unit 1, fractures with sediment filling were found at the reactor site at a maximum depth of about 5 m below the original rock surface, and at the turbine site at approximately 2.5 m. According to the construction engineers at Forsmark, the horizontal and subhorizontal fractures and sediment filling at Unit 1 show about the same pattern of behaviour as at Units 2 and 3. At the water tower rock drillings showed sediment-filled fractures not far below the rock surface.

In the surge basin of Units 1 and 2, horizontal and subhorizontal fractures filled with sediment material were found about 5 m below the original rock surface, the basin being excavated to a depth of approximately 20 m. The horizontal and subhorizontal fractures on the western wall of the basin are shown in Fig. 34. The two surge basins provide valuable information on the depth reached by the sediment-filled fractures. In these two basins it can be established that no sediment fillings occur on greater depth than 13 m below the rock surface. Horizontal and subhorizontal fractures containing sediment material were observed on all the wall faces in the storage basin for industrial water (Fig. 48). The deepest lying fracture with sediment filling was here found about 4 m below the rock surface the bottom of the shafts being about 8 m down.

Figure 49 shows two sections of the inlet channel, along



Fig. 39. A section of the eastern shaft wall of the inlet channel. One of the horizontal fracture occurring on the wall face represents the 820 mm maximum thickness of filling within the whole Forsmark area. A lower horizontal fracture contains sediment filling with a maximum thickness of roughly 350 mm. Photograph by Göran Hansson/N.

which sediment-filled fractures were plotted and recorded. Horizontal and subhorizontal fractures filled with sediment were seen on the wall faces along these mapped sections and in the extension of the shaft walls in the inlet channel. The survey results will be discussed in the next section.

The general behaviour of the sediment filling in the horizontal and subhorizontal fractures

The general behaviour of the sediment filling in the horizontal and subhorizontal fractures is relatively similar within the Forsmark area, although marked differences occur locally. In order to illustrate the similar behaviour of the sediment filling and the local variations, survey results from several shaft walls in the area will be reported. With this in mind, shaft walls at Unit 3 were selected together with two wall sections in the inlet channel. This selection is also intended to reveal possible variations with regard to orientation of individual walls by means of survey results from shaft walls striking N36°W and N54°E.

Figure 50 illustrates the fracture behaviour on the wall

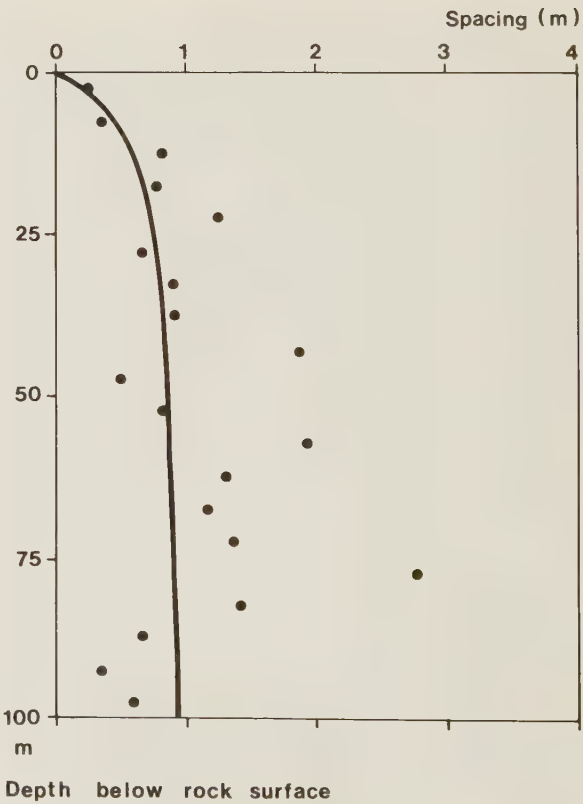


Fig. 40. The mean spacing of fractures intersecting the horizontal plane at angle less or equal to 20°, plotted against the drilling depth of the borehole DBT3.

face marked A in Fig. 17. On the occasion of the survey, the wall was about 90 m long with a mean height of approximately 2.3 m below the original rock surface. The strike direction of the wall is N36°W. In addition to horizontal and subhorizontal fractures, vertical and sub-vertical fractures occur on the wall face, striking mainly NE–SW and E–W. There are also vertical fracture planes which indicate fractures with a strike direction parallel to the direction of the wall. The dip angle of the horizontal and subhorizontal fractures is in the range of 0–10° with a dip tendency to the north-east. Much of the upper part of the rock mass is heavily fractured with both horizontal and vertical fractures resulting in, mainly, rectangular blocks.

A gently undulating horizontal fracture runs along the 90-m-long shaft wall, which also contains sediment material throughout its length. The sediment filling chiefly consists of silty to clayey silty material. According to the photograph in Fig. 61 the fracture filling at points J3, J4 and J5 (cf. Fig. 50) contains coarser material, and the sand fraction and current bedding can be seen too. Such an observation was also reported in Stephansson and Ericsson (1975:91, 94). The sediment filling, may contain rock fragments chiefly where the fracture aperture are relatively small. The thickness of the sediment filling along the horizontal fracture varies from a few to about 200 mm. This variation in thickness is illustrated in Fig. 51. The maximum fracture aperture and thickness of the sediment filling are about 190 mm at point A, almost in the middle of the photograph in Fig. 51. At points B and C, the fracture aperture is only a few millimetres, whereupon the aperture increases gradually on both sides of the cut-off.

The diagram of fracture behaviour on the wall face shows that the continuous horizontal sediment-filled fracture disappears into the rock surface at the termination of

the shaft wall. The other sediment-filled horizontal and subhorizontal fractures on the wall face are marked in Fig. 50. The filling material in these fractures is similar to that of the continuous horizontal fracture. However, the filling of these fractures is considerably less ranging from a few to a maximum thickness of 50 mm. One vertical fracture showed fillings of sediment material similar in composition to the sediment fillings above described. However the latter fracture contains too small quantities of filling material to confirm whether or not it really is a sediment material of the same composition as the other fillings.

A sketch map of the behaviour of fractures on the shaft wall marked G in Fig. 17 is given in Fig. 52. The strike direction of the wall is N36°W. The joint pattern is distinguished by a number of horizontal and subhorizontal fractures surmounting each other and, on the whole, a continuous horizontal fracture. These fractures intersect diverse vertical fractures with strike directions of NE–SW and E–W. Furthermore vertical fractures occur with a strike direction parallel to the direction of the shaft wall.

On comparison with shaft wall A, the behaviour of the horizontal and subhorizontal fractures differs at some points from that of the sediment fillings. There was a local heavily fractured zone in the uppermost part of the rock mass at shaft wall A, but this type of heavy fracturing is not seen on this wall face. Below the mean level of the continuous horizontal fracture on shaft wall A, only isolated horizontal fractures occur. Moreover, shaft wall G is characterized by a continuous horizontal fracture, but the horizontal and subhorizontal fracturing are more common below the mean level of the main fracture. The most striking difference between the two shaft walls is the thickness of the sediment filling. The maximum thickness of the filling material on shaft wall G is only about 15 mm with a mean of 8 mm, compared with a maximum of almost 200 mm at shaft wall A. The sediment filling in the fractures on shaft wall G may be described as clayey silt and no current bedding could be observed, the material showing an uniform fine-grained composition. Thus a continuous horizontal fracture filled with sediment is visible on those two shaft walls, but there is a marked difference in thickness of the fillings. Furthermore, sediment-filled horizontal and subhorizontal fractures are in contact with both the rock surface and other sediment-filled fractures. Horizontal fractures intersect vertical fractures on the two shaft walls but no sediment-bearing vertical fracture could be seen on shaft wall G.

Figure 53 gives a diagram of fracture behaviour on a 60-m-long shaft wall marked L in Fig. 17. The shaft wall, which has a strike direction of N54°E is characterized by partly filled, partly unfilled discontinuous horizontal and subhorizontal fractures, and by continuous and discontinuous vertical fractures. The vertical fractures comprise fractures striking NW–SE (Joint Set 2), NE–SW (Joint Set 3) and various random joints. The dip angle of the horizontal fractures is in the range of 0–10° with a north-eastern dip tendency. Fracture surfaces parallel to the strike direction of the shaft wall indicate vertical fractures with a corresponding strike direction. Locally, the rock mass is heavily fractured, in the form of a vertical fracture zone, and shows dense horizontal fractures in places.

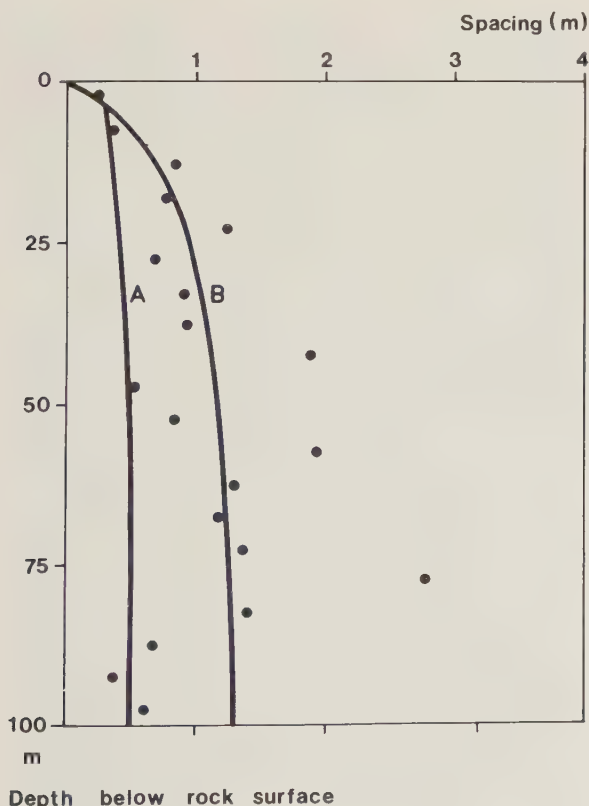


Fig. 41. The spacing in horizontal and subhorizontal fractures zones (A), and of fractures in the more intact rock (B) plotted against the drilling depth of the borehole DBT3.

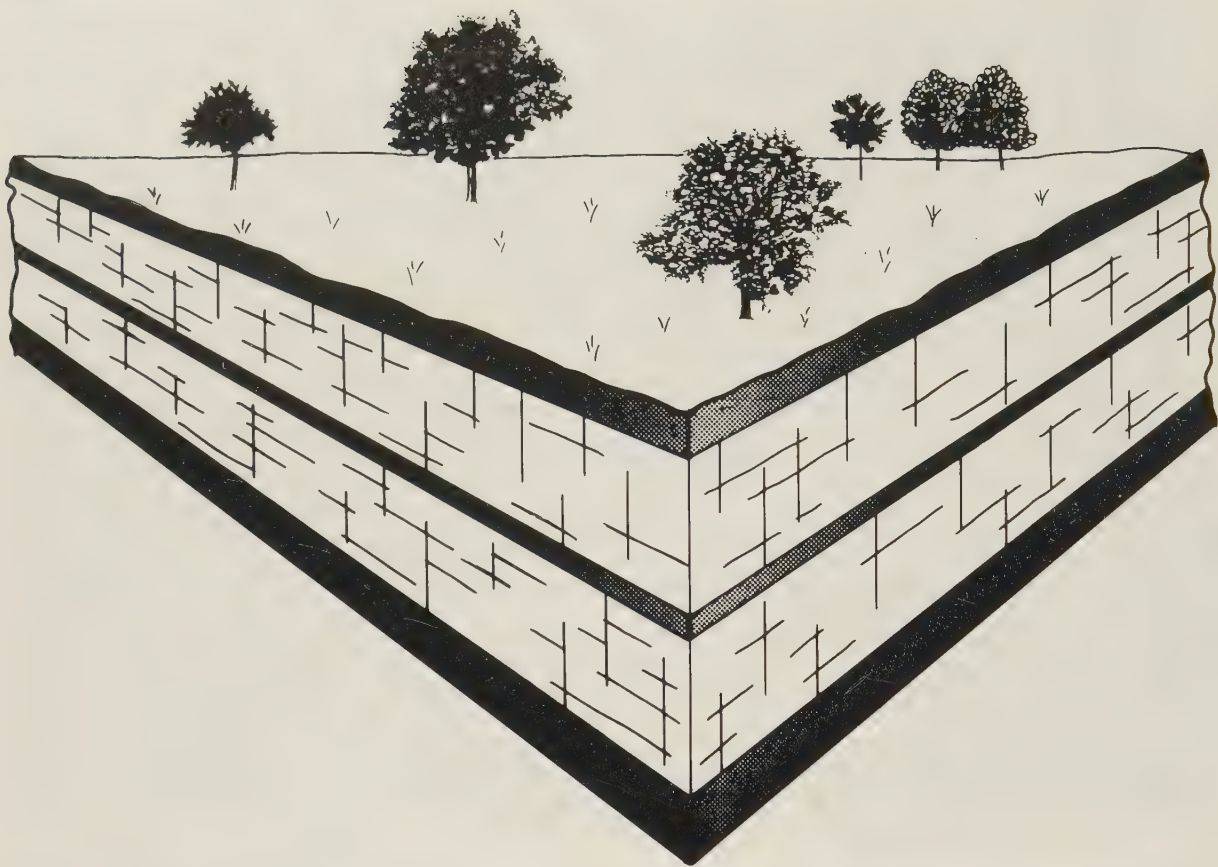


Fig. 42. A schematic block diagram showing the principle of the extension on depth of the horizontal and subhorizontal fracture zones in the Forsmark area.

In comparison with shaft walls A and G, the horizontal sediment-bearing fractures are more frequent on this wall. No continuous sediment-filled horizontal fracture exists on the shaft wall L, but horizontal fractures about 35 m long are seen. The thickness of the sediment fillings is here much greater than on shaft wall G, reaching a maximum of 170 mm, but shaft wall L does not show so high a mean as is the case on shaft wall A. As on shaft walls A and G, the terminations of the horizontal and subhorizontal fractures are about the same, touching the rock surface and in collision with each other but also they fade and disappear in the rock matrix. As shown in Fig. 53, three horizontal fractures with sediment filling intersect a vertical fracture zone striking NW–SE. The thickness of the sediment filling at the intersection is about 5 to 10 mm and the fracture fillings could be discerned along the full width of the fracture zone. Furthermore some vertical fractures contain sediment fillings about 1–2 mm thick, but the material in the vertical fractures appears only below the level of the uppermost horizontal fracture. The sediment filling in the fractures on shaft wall L consist chiefly of a silty to clayey-silty material and no indications of current bedding could be distinguished. However, rock fragments in some of the horizontal and subhorizontal fractures could be seen.

Horizontal and subhorizontal fractures on a shaft wall face (Fig. 36) marked B in Fig. 17 were described in the previous chapter. The wall has a strike direction of N36°W and a mean height of about 7.5 m. The steeply dipping

fracture zone which intersects the rock mass has a strike direction approximately NE–SW. The vertical fractures belong to the sets of joints 1 and 3, and random joints occur too. The sediment filling which mainly consist of clayey silt have a maximum thickness of 50 mm. Three of the horizontal sediment-filled fractures intersect the fracture zone while one gradually fades out and terminates at the contact with the vertical fracture. The thickness of the sediment filling in the horizontal fractures at the intersection of the fracture zone amounts to a few mm.

The horizontal and subhorizontal sediment-filled fractures on shaft wall C in Fig. 37 present a pattern reminiscent of the fractures on the aforesaid wall face. The distance between the two shaft walls is about 15 m (Fig. 17), and both strike N36°W. The fracture behaviour on shaft wall C was also described in the previous chapter and horizontal and subhorizontal sediment-filled fractures intersect a steep dipping fracture zone striking NE–SW.

Thus fracture behaviour is very similar on the two wall faces. The vertical fractures can be related to the Joint Sets 2 and 3 and random joints occur too. Consequently, no fractures belonging to Joint Set 1 are visible on the wall face. The thickness of the sediment filling on shaft wall C is somewhat greater than on shaft wall B, with a maximum thickness of approximately 100 mm. The sediment filling in this fracture does not decrease in thickness when crossing the fracture zone, as is the case in the other fracture fillings here and on shaft wall B. The sediment filling in this



Fig. 43. The shaft wall marked U in Fig. 17 showing a subhorizontal sediment-filled fracture terminating at the bedrock surface and also intersecting a dike of pegmatite. Photograph by Göran Hansson/N.

particular fracture on wall face C is indicated in Fig. 37 and the material shows a very fine-grained composition, i.e. about 99 % of the material is less than 0.063 mm in grain-size. Two vertical sediment-filled fractures were found on this wall face. These fractures however contain only a very thin filling of sediment. With the exception of a few which contain a fairly thick sediment filling, sediment filling in vertical fractures throughout the Forsmark area is characteristically very thin.

Figure 43 represents a shaft wall with a limited number of horizontal and subhorizontal fractures, and thereby a limited occurrence of sediment filling. This shaft wall, marked U in Fig. 17 has a strike direction of N54°E. This type of limited occurrence of horizontal and subhorizontal fractures in the superficial rock mass within the Forsmark area is uncommon.

The occurrence of horizontal and subhorizontal fractures and the presence of sediment filling on wall face Q in Fig. 54 are the reverse of these features on wall face U. A relatively thick layer of till superposes the rock surface of this shaft wall, and almost all of the horizontal and subhorizontal fractures contain filling material of sediment, although of limited thickness. The horizontal set excluded, Joint Set 3 is the predominant set on the shaft wall shown in Fig. 54 which means fractures with a strike direction NE–SW.

The shaft walls described so far illustrate the occurrence of sediment filling in horizontal and subhorizontal frac-

tures within the area of Unit 3, and the account gives an idea of the frequency of horizontal fractures in the area. Hence, there is a similarity between the occurrence of sediment filling in the horizontal and subhorizontal fractures and in diagonal fractures running from one horizontal fracture to another. In addition there are examples of vertical fractures containing sediment, but this should be regarded as a surface coating rather than a fracture filling. The continuous horizontal fracture observed on shaft wall A represents the thickest sediment filling in the area of Unit 3 and also has the greatest mean thickness of all the horizontal fractures there. Furthermore, graded bedding could only be observed in the sediment filling of this horizontal fracture. Moreover, the fracture fillings consists mainly of a silty and a clayey silty material but rock fragments were found as well.

Figure 55 illustrates the occurrence of horizontal and subhorizontal fractures and the presence of sediment filling on one section of the eastern shaft wall of the inlet channel. The mapped section marked CE in Fig. 49 has a length of about 100 m and the shaft wall a mean height of approximately 5.5 m with a maximum of 7.5 m. This wall, which has a strike direction of N54°E, presents the thickest sediment filling to be found throughout the Forsmark area. The rock mass is composed of gneiss granite with rare dikes of greenstones and pegmatites. As shown in Fig. 55, the upper part of the rock mass is heavily fractured. This heavy fracturing is illustrated in Fig. 31, where both



Fig. 44. A horizontal fracture terminating on contact with a vertical fracture. Photograph by Göran Hansson/N.

horizontal and vertical fractures exhibit a close spacing. The shape of the individual blocks may be designated irregular. These severely fractured sections of the rock mass contain fractures which are almost invariably filled with sediment. However, it is difficult to comprehend the extent of the horizontal fractures, so that the individual horizontal fractures in the heavily fractured zones are not marked.

All the horizontal and subhorizontal fractures on the wall face in Fig. 55 present sediment filling of considerable thickness up to a maximum of 820 mm. Another horizontal fracture on the wall face has a maximum thickness of the sediment filling of 625 mm, while others contain sediment filling about 200–300 mm thick (cf. Fig. 39). Several of the horizontal and subhorizontal fractures filled with sediments are connected by diagonal fractures, while others terminate at the rock surface.

Apart from sediment filling in the horizontal and subhorizontal fractures some vertical fractures contain sediment as shown in Fig. 56. The aperture of the upper part of the vertical fracture is no more than a few mm, and contains a thin layer of sediment, but at the contact with the horizontal fracture, the aperture increases rapidly, as does the thickness of the sediment layer. The increase in the fracture aperture may be partly due to blasting but the fracture is filled with sediment roughly 20 mm thick from a level of 0.75 m above the upper edge of the horizontal fracture. Upwards from this level, the aperture and thickness

of filling gradually decreases. As appears from Fig. 39, which shows the thickest sediment filling, a vertical fracture running from the uppermost to an underlying horizontal fracture also has a fracture filling of sediment material. On the whole, the material in the sediment-filled fractures may be described as clayey silt but coarser material such as sand is found as well, and locally also current structures, especially in those fractures which have the thickest sediment filling.

Figure 57 represents the fracture behaviour and occurrence of sediment filling along a 500-m-long section of the western wall of the inlet channel. The mapped section is marked CW–CW in Fig. 49. There the rock mass is made up of gneiss granite and a number of dikes of pegmatites and greenstones occur on the shaft wall which is also intersected by a crushed zone. The sediment filling on this wall face is not as thick as found on the eastern inlet wall. However, sediment fillings may be approximately 300 mm thick in places, but was here washed out after the excavation of the shaft. Some fractures are partly filled with sediment which may also be due to wash-out after blasting. Figure 58 gives an example of such a wash-out.

The behaviour of the sediment fillings on the wall faces in the storage basin for industrial water (Fig. 2) was previously described by Stephansson and Ericsson (1975) and A. Carlsson and T. Olsson (1976b). According to the former (1975:91) a subhorizontal fracture filled with sediment found about 4 m below the rock surface, and



Fig. 45. Two subhorizontal fractures terminating on contact. Photograph by Göran Hansson/N.

recurred on all the wall faces in the basin. The maximum aperture of the fracture measures to about 500 mm. More fractures containing sediments 200 mm thick were discovered on the basin walls. The material is mainly composed of the silt fraction, but as Stephansson and Ericsson (1975:91) point out, the sediment becomes richer in clay as the fracture apertures narrow. They go on to state that the sediments show a marked periodicity with about 50 varves in the widest part of the main fracture, the thickness of the varves varying from a few mm to a few cm. Figure 48 is a general view of the storage basin for industrial water, showing the occurrence of horizontal and subhorizontal fractures filled with sediments.

To sum up, as regards the filling the general behaviour on the individual shaft walls within the Forsmark area is similar, but the number of sediment-filled fractures and the thickness of the fillings may vary considerably from one place to another. However, these variations cannot be said to be differences between shaft walls, but may occur on one and the same, as well as on different shaft walls. The orientation of the walls seems irrelevant to the occurrence of horizontal and subhorizontal fractures. Nor does the orientation of the shaft walls seem at all important for the occurrence or behaviour of sediment filling. Yet the sediment-filled fractures are concentrated to the uppermost part of the rock mass, i.e. the upper 2–3 m on each shaft wall, although fractures containing sediment filling are found below this level and the deepest lying sediment-

filled fracture recorded in the area was found about 13 m below the original rock surface. Where the rock mass is heavily fractured, a certain relationship prevails—although not invariably—between the occurrences and the thickness of sediment fillings.

Analyses of the sediment fillings

Grain-size distribution. — Samples from the sediment filling in the investigation area were collected in order to determine the grain size distribution. Figures 59 and 60 present cumulative frequency curves of the sediment material taken from the area of Unit 3, Unit 1, the inlet channel, and the storage basin for industrial water.

The samples J1–J6 were all collected in the continuous horizontal fracture on shaft wall A (Fig. 17) the respective sampling sites being marked in Fig. 50. The sediment sample J1 was collected about 0.75 m below the original rock surface. The thickness of the sediment filling is there about 100 mm and the material consists of a sandy silt. The sample J2 was collected roughly 1.25 m below the rock surface described as silty sediment. The thickness of the sediment filling here too is about 100 mm. The samples J3, J4 and J5 were taken from sites marked on Fig. 61, i.e. J3 was collected above the sand layer and consists of a sandy silt, sample J4 comes from below the sand layer close to the fracture surface and comprises clayey silt. The

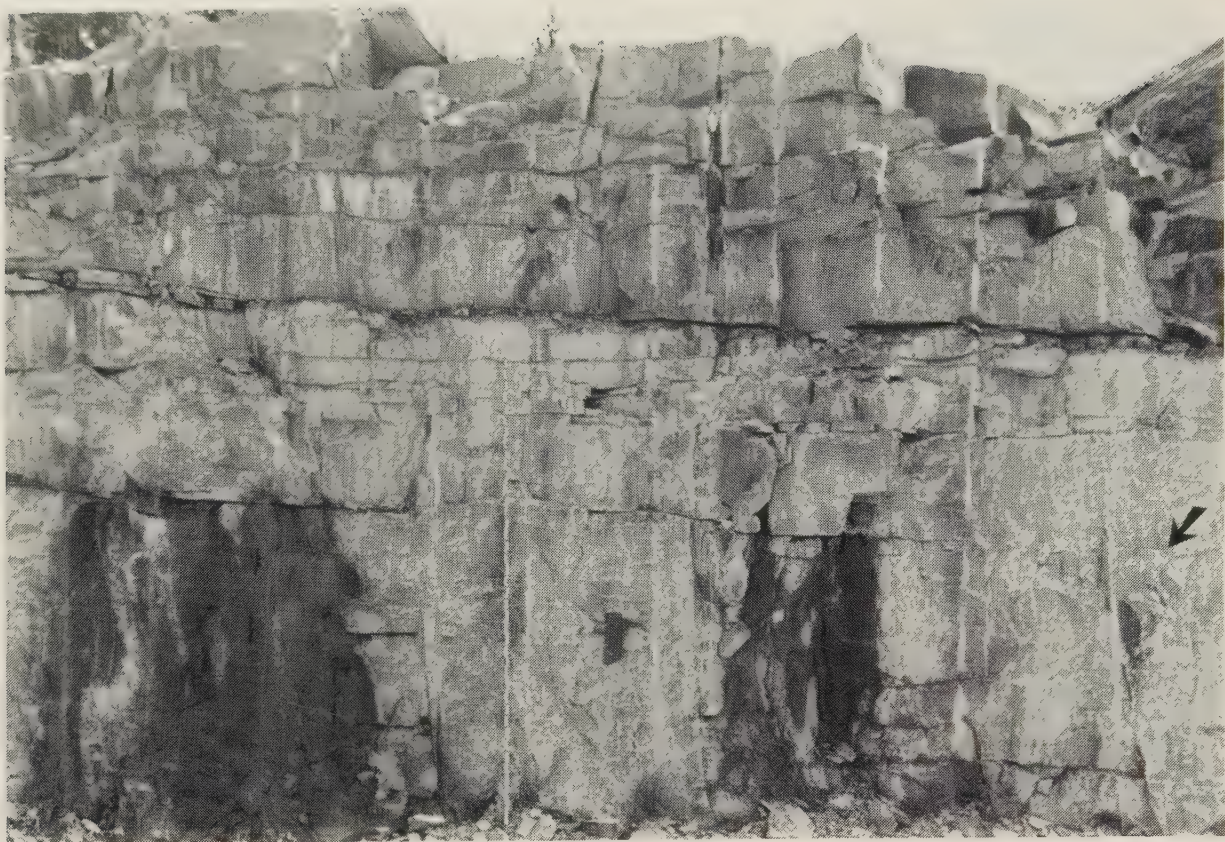


Fig. 46. A horizontal fracture which gradually fades into the rock matrix. Photograph by Göran Hansson/N.

Table 8. Grain-size distribution of the sediment samples J7, J8 and J10. The sampling sites are shown in Fig. 17.

Sample no.	Sampling depth m							Weight per cent Fractions in mm			
		8	8–5	5–4	4–2	2–1	1–0.5	0.5–0.25	0.25–0.125	0.125–0.063	<0.063
J7	1.25	39	0.52	0.17	0.39	0.15	0.11	0.11	—	0.52	58.9
J8	2.40	0	0	0.13	0.06	0.01	0.04	0.07	—	0.4	99.2
J10	1.20	0.87	0.06	0.14	0.10	0.06	0.22	0.55	1.63	6.47	89.8

sample J5 was collected in the sand layer so that the sand fraction predominates. All these samples were collected at a depth of about 1.7 m below the rock surface and the sediment filling is here approximately 170 mm thick. The sediment sample J6 too was collected in the main fracture on shaft wall A, the site being about 0.6 m below the rock surface. Here, the thickness of the filling is about 200 mm and the material consists of clayey silt.

No hydrometric analyses of the sediment samples J7, J8, and J10 from the area of Unit 3 (Fig. 17) were made, so the grain-size distribution of material greater than 0.063 mm is presented in Table 8. The sample J7 was collected from an approximately 150 mm-thick sediment filling at a depth of 1.25 m below the rock surface and the material smaller than 0.063 mm amounts to about 59 %. The sample J8 comes from a sediment filling about 150 mm thick roughly 2.4 m below the rock surface. Almost 99 % of the material falls short of 0.063 mm while 90 % of sample J 10 is of this size.

The sediment samples J 11 and J 12 were collected in the area of Unit 1 and consist of clayey silt. The samples were taken from a horizontal fracture running 1.5 m below the rock surface which contains sediment filling 100 mm and 250 mm thick respectively. In the storage basin for industrial water, two samples of sediment filling (J13 and J14) were collected in a horizontal fracture running 4 m below the rock surface with a maximum thickness of 500 mm. The material of the two samples is silt. Two samples (J15 and J16) were also collected from fractures on the eastern wall of the inlet channel at depths of 3.5 and 4.6 m respectively, where the thickness amounted to about 340 and 230 mm respectively. The sampling sites are shown in Fig. 55. The material of the samples can be characterized as clayey silt.

The analyses of the grain-size distribution of the sediment material in the horizontal and subhorizontal fractures in the area revealed that the composition is relatively homogeneous in the shaft where samples were collected. In



Fig. 47. Horizontal fractures running parallel to the bedrock surface. Photograph by Göran Hansson/N.

Table 9. Calcium content of some sediment samples collected in the area of Unit 3. The sampling sites are shown in Fig. 17.

Sample no.	Type of sediment	Sampling depth m	Fracture aperture mm	Calcium content (%)			
				1–0.5	Fractions in mm		
					0.25–0.125	0.125–0.063	<0.075
J1	sandy silt	0.75	100	1.8	1.4	—	7.2
J2	silt	1.25	100	—	—	—	12.3
J3	sandy silt	1.40	170	0.8	2.1	—	6.8
J4	clayey silt	1.40	170	—	—	—	9.1
J5	sand	1.40	170	0.9	1.8	—	4.1
J7	silt	1.25	150	—	2.4	—	—
J10	silt	1.20	180	—	1.4	1.7	—

other shafts the sediment fillings were examined by eye and on the basis of the laboratory analysis and the visual examinations we may say that the composition is similar throughout. In the storage basin for industrial water, Stephansson and Ericsson (1975:93) also analysed the grain-size distribution of three sediment samples, which produced similar results i.e. the silt fraction predominates. However, there is a tendency to a finer grained composition when the fracture aperture decreases. This tendency prevails along one and the same fracture, as well as on comparison of fractures with a different width of aperture. The result of the grain-size analysis does not suggest that the sediment fillings contain rock fragments because the sieving only concerned the grain-size distribution of the sediment material.

Analyses of the contents of calcium, feldspar and heavy minerals. — Analyses of the calcium content were made on the sediment samples J1–J5, and J7 and J10 according to the method described in connection with similar analyses of the till samples. The results are given in Table 9 and the sampling sites, types of soil, sampling depths are the same as for the grain-size distribution.

The calcium content of all the fractions of the sediment samples, except the material less than 0.075 mm, is less than 3% and of the finest fraction 13%. Thus, the calcium content of the material less than 0.075 mm is much higher than in the other fractions. Stephansson and Ericsson (1975:93) determined the organic carbon content of the finest grained sediment in one sample collected in the storage basin, as about 1 %, the CaCO_3 content being



Fig. 48. A general view of the storage basin for industrial water showing sediment-filled horizontal and subhorizontal fractures. Photograph by Göran Hansson/N.

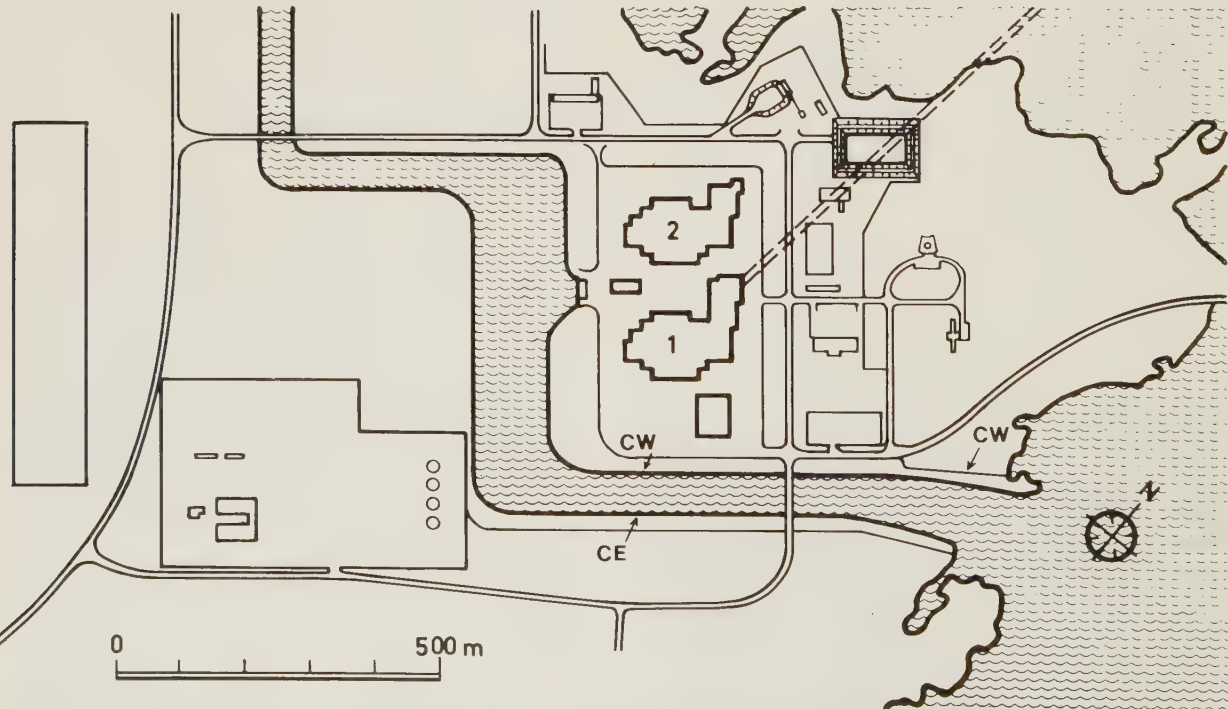


Fig. 49. A chart of part of the construction area. The two sections of the inlet channel surveyed for horizontal and subhorizontal fractures and sediment filling are marked.

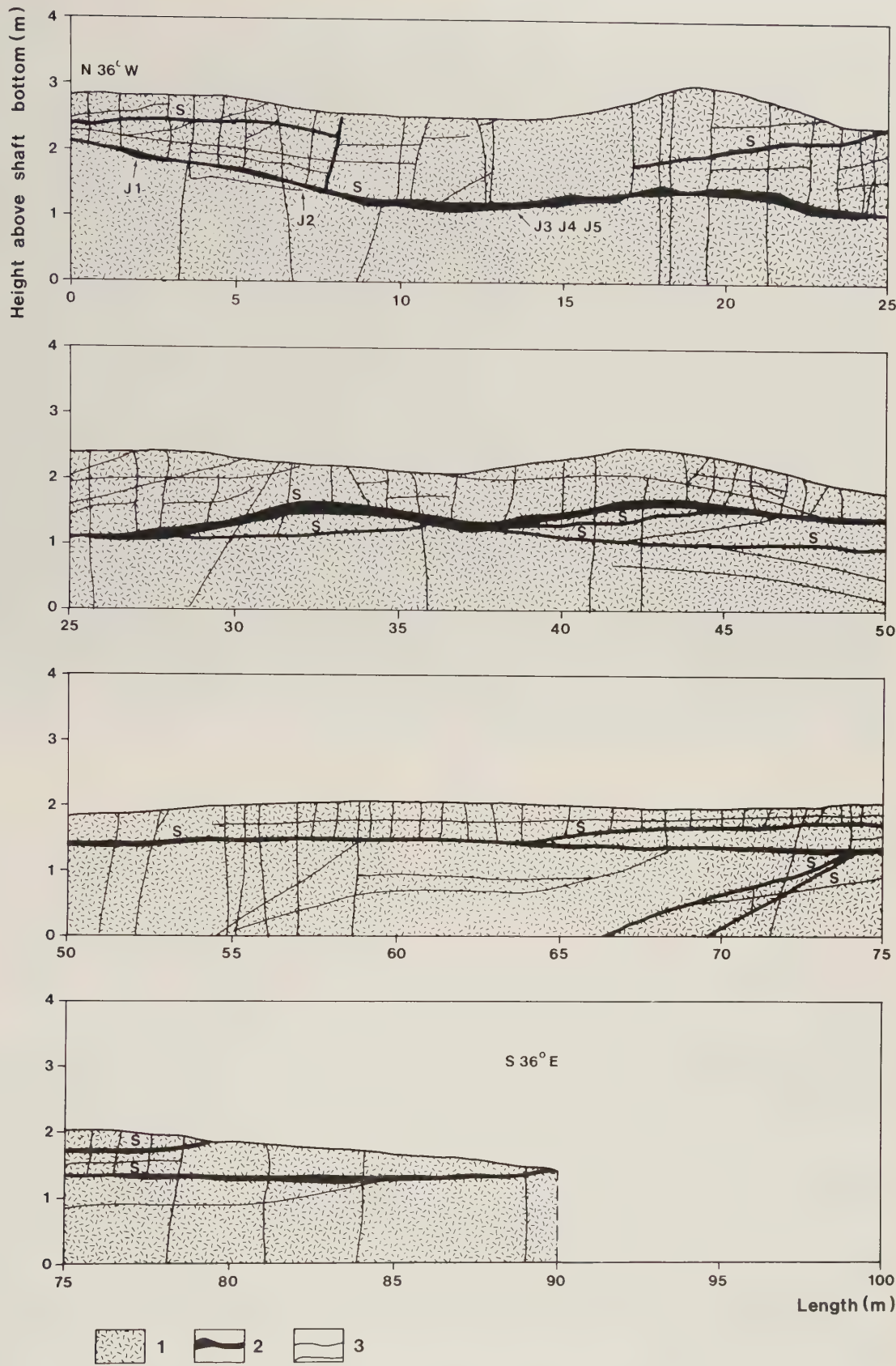


Fig. 50. Fracture behaviour and the occurrence of sediment fillings on the shaft wall marked A in Fig. 17. 1. Gneiss granite. 2. Sediment-filled fracture. 3. Fracture without sediment filling.



Fig. 51. A section of shaft wall A showing the variation in the thickness of the sediment filling. The aperture value at point A is about 190 mm and at the points B and C only a few mm. Photograph by Göran Hansson/N.

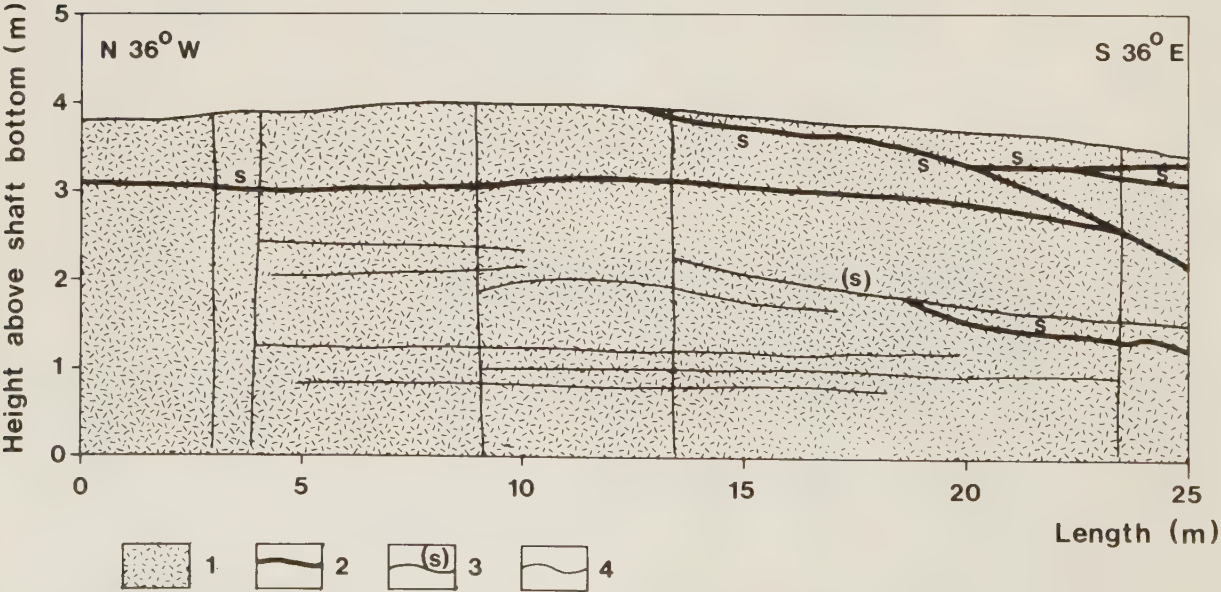


Fig. 52. Fracture behaviour and filling material of sediments on the shaft wall marked G in Fig. 17. 1. Gneiss granite. 2. Sediment-filled fractures. 3. Fractures partly filled with sediment. 4. Fractures without filling material of sediment.

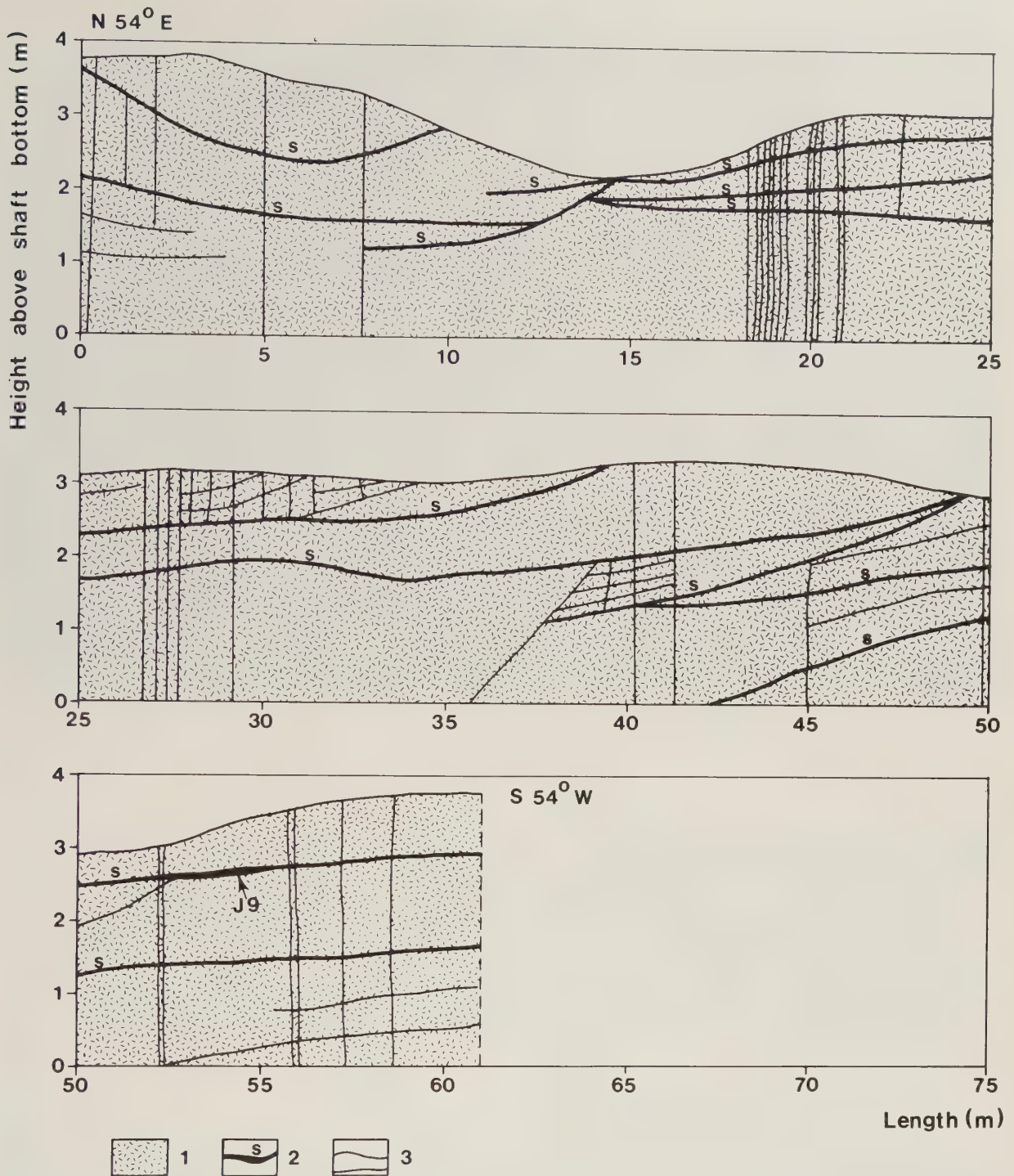


Fig. 53. Fractures and sediment filling on the shaft wall marked L in Fig. 17. 1. Gneiss granite. 2. Sediment-filled fracture. 3. Fractures without filling material of sediments.

about 2 %. Thus, the determinations of the calcium content in the finest grained sediment samples presented here show a relatively high content. Stephansson and Ericsson (1975:93) also say, that the overlying till contains a small amount of CaCO_3 . A comparison of analyses of the sediment and the till samples collected in the area of Unit 3, demonstrates that the content of calcium is of approximately the same, i.e. about 2 %. No analyses of the finest grained parts of the till were made, and no com-

parison between the till and the sediment as regards material less than 0.075 mm can therefore be made.

The content of heavy minerals and feldspar in the sediment was determined in sediment samples J1–J5 and also a rock sample of the gneiss granite according to the method for analysis of the till samples. The result of the analyses is shown in Table 10.

The contents of feldspar and heavy minerals in the sediment are appreciably lower than in the till samples



Fig. 54. A section of the shaft wall marked Q in Fig. 17 showing a heavily fractured rock mass. Photograph by Göran Hansson/N.

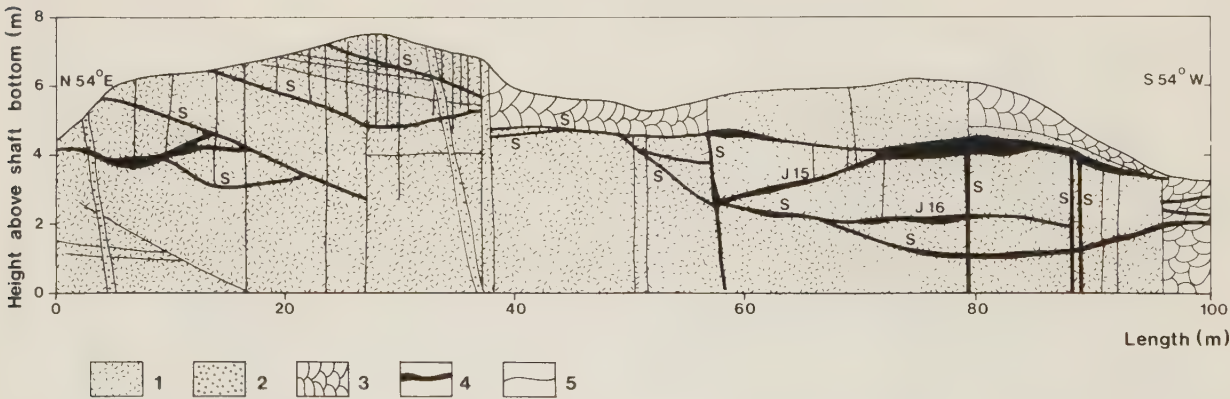


Fig. 55. Sketch of the fractured rock mass of a section of the eastern shaft wall of the inlet channel marked CE in Fig. 49. 1. Gneiss granite. 2. Greenstones. 3. Crushed or heavily fractured zones. 4. Sediment-filled fracture. 5. Fractures without filling material of sediments.

while the rock sample shows a consistently higher content of heavy minerals than the till and the sediment samples. Table 10 illustrates the degree of roundness of some sediment samples. There is no significant difference between the sediment material and the till shown in Table 1.

Hydraulic conductivity determinations. Table 11 reports the result of the determinations of the hydraulic conductivity of some sediment samples, by using standard

permeability apparatus, as being in the range of $4.2 \cdot 10^{-6}$ m/s to $1.7 \cdot 10^{-8}$ m/s. Regarding the composition of the material the values of the hydraulic conductivity presented here are in agreement with the rough calculation given by Fagerström and Wiesel (1972:9).

The samples used for determination of hydraulic conductivity are the sediment samples J1–J6 collected on shaft wall A at Unit 3 and one of those collected at the site of the turbine building at Unit 1. Table 11 reveals that samples J6 and J4 show the lowest values of hydraulic conductivity, i.e. $1.7 \cdot 10^{-8}$ m/s and $1.9 \cdot 10^{-8}$ m/s respective-



Fig. 56. A section of the eastern shaft wall of the inlet channel showing the occurrence of sediments in a vertical fracture. Photograph by Göran Hansson/N.

Table 10. Analyses of the contents of heavy minerals and feldspar of some sediment samples, and one rock sample of gneiss granite. The degree of roundness is indicated by (R) in the table. Roundness: I = angular, II = subangular, III = subrounded. The type of sediment, average sampling depth and fracture aperture are demonstrated in Table 9: All of the samples are collected in the area of Unit 3 (Fig. 17).

Sample no.	1–0.5	Heavy minerals (%) Fractions in mm			1–0.5	Feldspar (%) Fractions in mm		
		0.5–0.25	0.25–0.125	0.125–0.063		0.5–0.25	0.25–0.125	0.125–0.063
J1	0.7	—	3.2	—	26.6	—	26.7	
J1 (R)	II–III (R)		II (R)					
J2	—	—	3.3	—	32.7	—	30.9	
J2 (R)	I (R)		III (R)					
J3	0.6	—	3.4	—	17.1	—	30.6	
J3 (R)	I (R)		I–II (R)					
J4	1.7	—	3.3	—	27.4	—	20.9	
J4 (R)	I (R)		II (R)					
J5	5.2	—	0.6	—	30.1	—	27.4	
J5 (R)	III (R)		III (R)					
J10	—	1.4	1.9	2.9	—	27.7	25.7	14.6
Rock S.		11	12	36	—	32	24	28

ly. The two samples J6 and J4 also have the finest grained material, clayey silt, while J5, which has the highest value for hydraulic conductivity, $4.2 \cdot 10^{-6}$ m/s consists chiefly of the sand fraction.

The sediment samples J1–J6 are disturbed samples and at laboratory determinations of hydraulic conductivity such samples may incorporate a number of sources of error which influence the result, shown by e.g. Bernell (1958:27–34), Knutsson and Morfeldt (1973:32–33) and Olsson (1979). Olsson (1979) gives some factors of

significance for the hydraulic conductivity of a soil, such as bedding, grain-size and grain-size distribution, degree of packing, water content and air content. The first three factors are described by Olsson (1979) as material constants inherent in the structure of the soil mass, while the others constitute variables not directly related to the properties of the soil material. Hence, the interior structure of a soil is crucial for the hydraulic conductivity. Olsson (1979) points out inter alia that the interior structure of the dis-solute mixture of a till in situ gives rise to a greatly in-

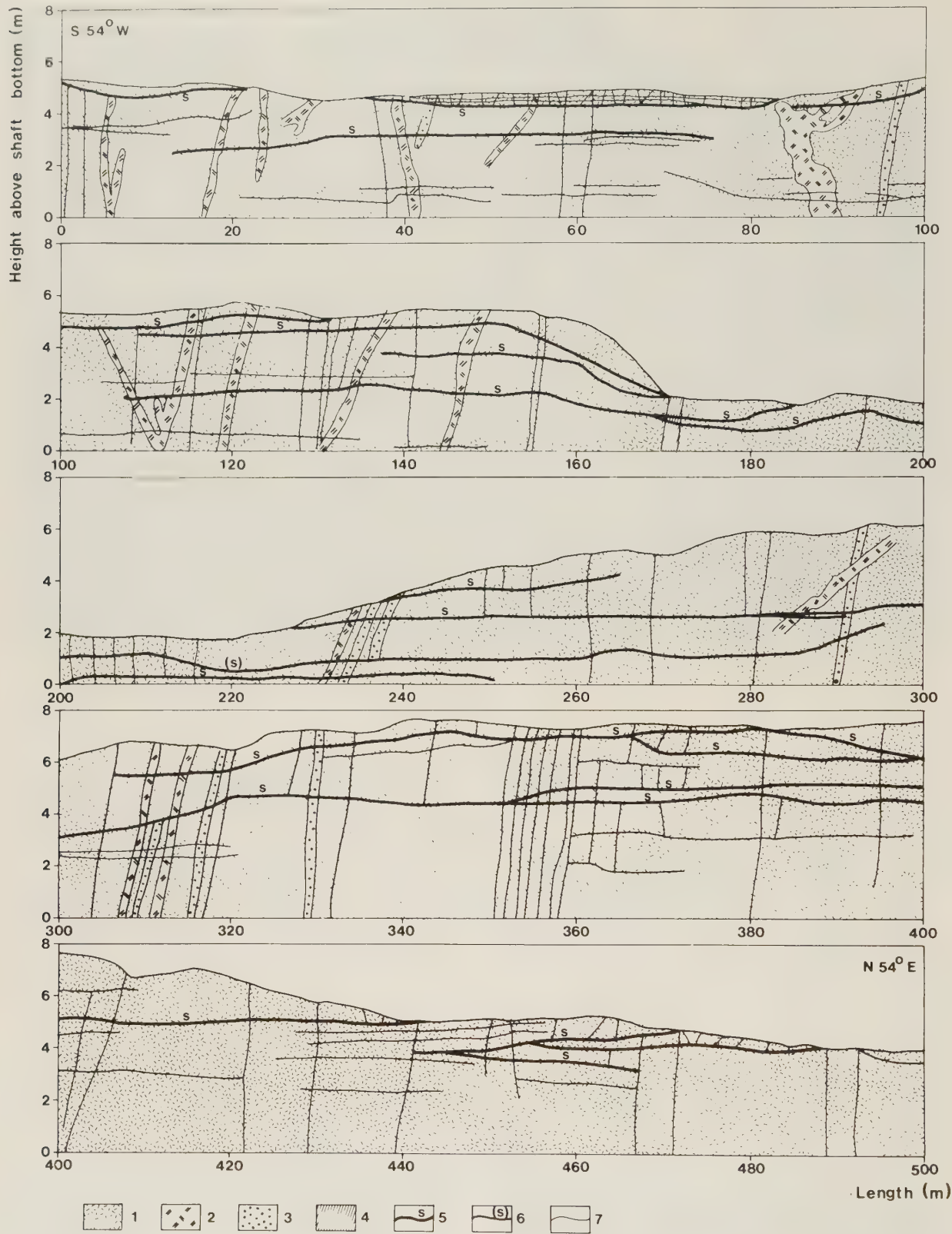


Fig. 57. Fracture behaviour and the occurrence of sediment fillings on a 500-m-long section of the western shaft wall of the inlet channel marked CW–CW in Fig. 49. 1. Gneiss granite. 2. Pegmatites. 3. Greenstones. 4. Crush zone. 5. Sediment-filled fracture. 6. Fracture partly filled with sediment. 7. Fracture without filling material of sediment.



Fig. 58. A section of the eastern inlet channel wall showing sediment filling in a horizontal fracture which has been partly washed-out after the excavation of the shaft. Photograph by Göran Hansson/N.

Table 11. Hydraulic conductivity values of some sediment samples.

Sample no.	Samling site	Average sampling depth m	Thickness of filling mm	Type of soil	Hydraulic conductivity m/s
J1	Unit 3	0.75	100	sandy silt	$1.1 \cdot 10^{-7}$
J2	Unit 3	1.25	100	silt	$5.5 \cdot 10^{-8}$
J3	Unit 3	1.40	170	sandy silt	$1.7 \cdot 10^{-7}$
J4	Unit 3	1.40	170	clayey silt	$1.9 \cdot 10^{-8}$
J5	Unit 3	1.40	170	sand	$4.2 \cdot 10^{-6}$
J6	Unit 3	0.60	200	clayey silt	$1.7 \cdot 10^{-8}$
J13	Unit 1	4.00	500	silt	$1.5 \cdot 10^{-7}$

creased value of the hydraulic conductivity as compared with the values determined on laboratory samples provided that the true conditions in situ are not simulated for the determination in laboratories. The same conditions may be applied to determination of hydraulic conductivity of sediments, in that the sediment like the till shows bedding and lenses, and here too, varves occur.

The sediment sample J3 was taken from a layer of silty sand, J4 in a clayey silt and J5 from the sand layer. The values for the hydraulic conductivity of each sample are $1.7 \cdot 10^{-7}$ m/s, $1.9 \cdot 10^{-8}$ m/s and $4.2 \cdot 10^{-6}$ m/s. The thickness of the sediment filling is 170 mm and of the sand layer (J5) at the sampling site about 40 mm. The thickness of the finer fraction (J4) is about 30 mm and of the somewhat coarser layer (J3) 100 mm. Hence, according to Terzaghi and Peck (1967:54), the hydraulic conductivity of the composite stratum is as follows:

$$k = \frac{1}{W_T} (W_3 k_3 + W_4 k_4 + W_5 k_5)$$

where W_T = the total thickness of the sediment filling (mm)

W_3 – W_5 = the thickness of each layer (mm)

k_3 – k_5 = the hydraulic conductivity of each layer (m/s)

This gives a value for the hydraulic conductivity of the composite stratum of $1.1 \cdot 10^{-6}$ m/s. If this value is compared with that of the sediment sample J2, which represents more homogeneous material with no distinct structures, the value of the hydraulic conductivity of the composite stratum will be seen to be 20 times greater than that of the sample J2. This state of affairs demonstrates the importance of the sand layer for the hydraulic conductivity of the total stratum. Similar conditions as regards the hydraulic conductivity of the till are documented in Olsson (1979).

The hydraulic conductivity of the till was determined on two till samples collected in the area of Unit 3, which show values of $1.7 \cdot 10^{-8}$ m/s and $5.5 \cdot 10^{-10}$ m/s respectively.

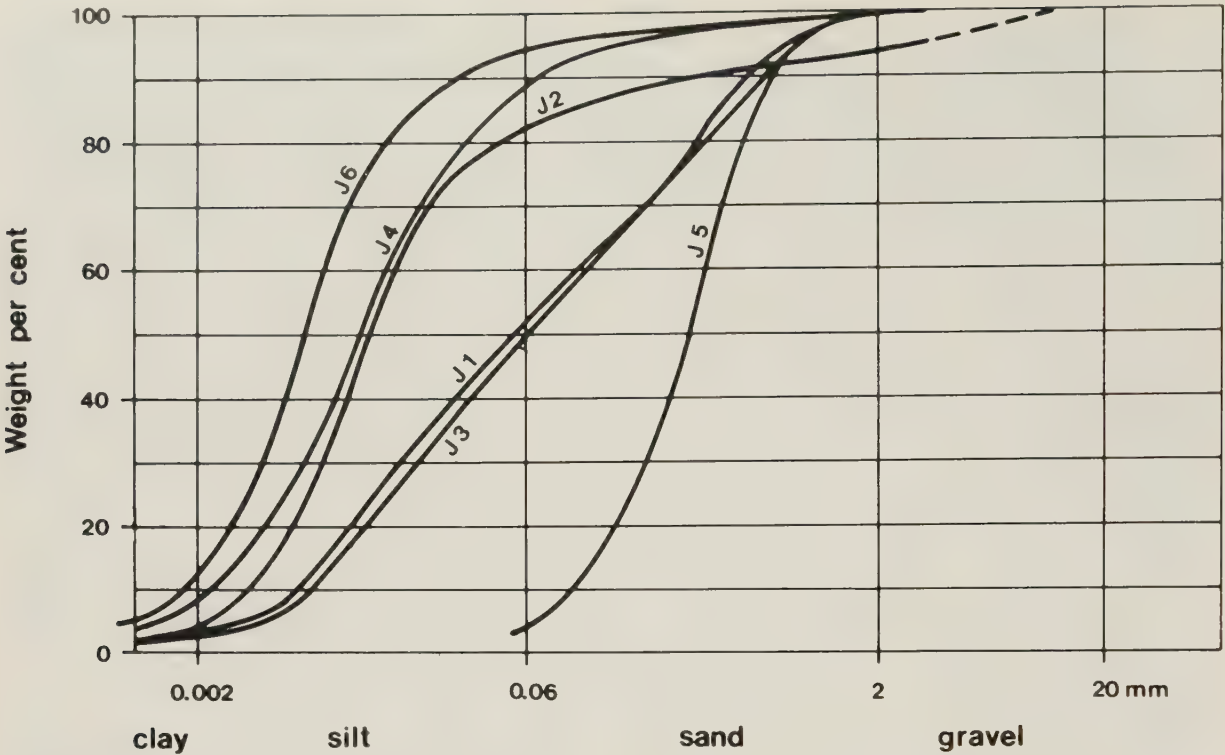


Fig. 59. The grain-size distribution of some sediment samples from the area of Unit 3.

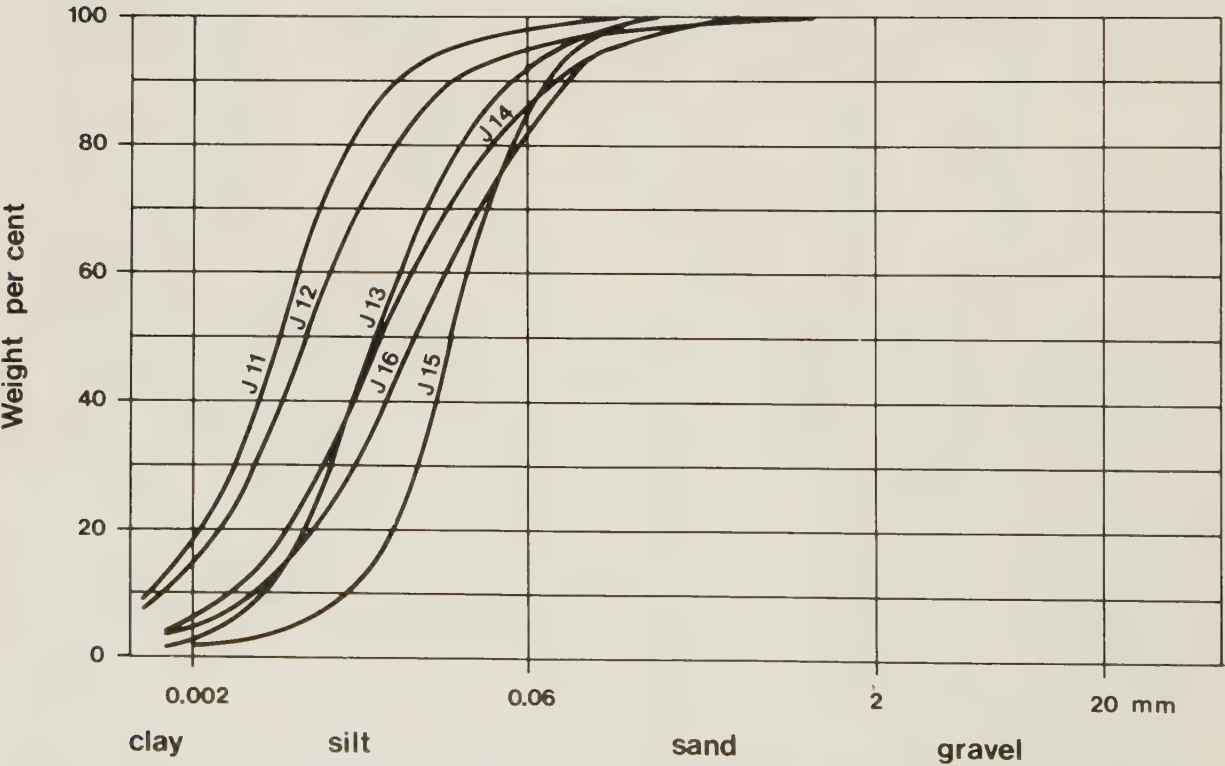


Fig. 60. The grain-size distribution of some sediment samples from the area of Unit 1, the inlet channel and the storage basin.

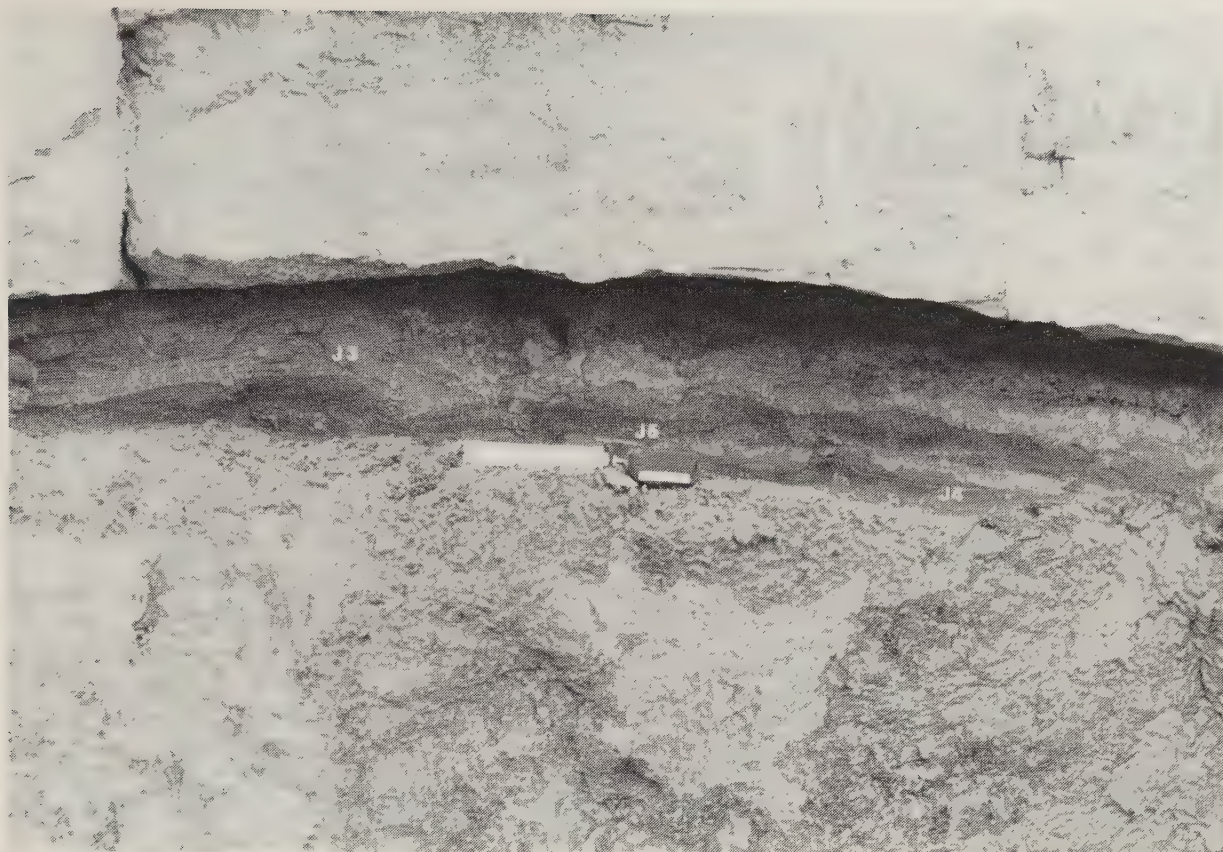


Fig. 61. The sediment filling in the main fracture on the shaft wall marked A in Fig. 17. The sampling sites of the sediment samples J3, J4, and J5 are indicated. Photograph by Göran Hansson/N.

Olsson (1979) points out that the value of the hydraulic conductivity determined in the laboratory is in the range of $5 \cdot 10^{-7}$ m/s for a sandy gravelly till to $5 \cdot 10^{-10}$ m/s for a clayey till. The two till samples tested here can be characterized as a sandy silty till.

Compression tests. In order to assess the compaction properties of the sediment filling in the horizontal and sub-horizontal fractures, undisturbed samples were collected in the storage basin for industrial water, the inlet channel and the site of the turbine building of Unit 1 (Fig. 2).

In connection with the determination of the compressibility of the sediment material, as in the case of other soil types, it is necessary to use undisturbed samples because the compressibility varies considerably with the degree of packing, and with the magnitude of the loading. The sediment material may be regarded as a plastic medium so that the deformations at the loadings are irreversible. Moreover a period of time prevails between the changes of loading and the deformations, and this may vary from a few minutes to decades according to the composition of the soil material and local conditions. This is described in more detail in e.g. Bernell (1958:45–52) who points out that the properties of the material and the time factor must taken into account in problems connected with the consolidation and the settling of the soil material.

The course of compression in two sediment samples is

illustrated by curves A and B in Fig. 62. Curve A represents a sediment sample from the storage basin, collected at a depth of approximately 4 m below rock surface. The material can be classified as silty sediment and corresponds to the cumulative frequency curve designated J14 in Fig. 60. Curve B in Fig. 62 represents a sample from the turbine site at Unit 1 collected at a depth of 1.5 m below the rock surface. The material can be characterized as clayey silt and is demonstrated by curve J11 in Fig. 60. The thickness of the sediment filling is 500 mm and 100 mm respectively.

The sediment sample from the storage basin was gradually subjected to an effective vertical normal pressure, the maximum pressure then amounting to 590 kN/m². The relative compression of the sample was 3 % at most with an original water content of 20 % (graph A). The sample from the turbine site at Unit 1 was gradually loaded to a maximum normal pressure of 3925 kN/m². The compression was then 7 % at maximum load with an original water content of 21 %. Graph B in Fig. 62 illustrates the course of settling in this sample.

Figure 63 shows the courses of settling in three undisturbed samples. The samples were collected in the inlet channel on the eastern shaft wall, the material being silt demonstrated by graph J16 in Fig. 60. The samples come from an approximately 230 mm-thick sediment filling in a subhorizontal fracture running about 4.6 m below the original rock surface (cf. Fig. 55). Curve C represents a sample collected vertically, while curves D and E depict

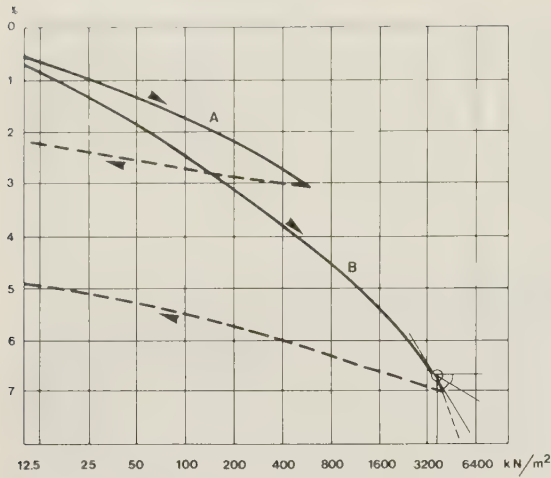


Fig. 62. Relationship between loading and compression. The course of compression in samples from the storage basin (A) and Unit 1 (B). The graphic solution of the Casagrande method is indicated (A. Carlsson and T. Olsson 1976b:77).

samples taken horizontally. The samples D and E were collected in a direction of N18°E and N72°W respectively. The three samples were gradually loaded to a maximum normal pressure of 4000 kN/m². The compression of sample C was then 3.9 %, of sample D 4.9 % and of the sample E 5.5 % at most with an original water content of 17 %, 19 %, and 19 % respectively.

As demonstrated by compression curve B, the curve has a relatively flat inclination at a loading value lower than about 3400 kN/m², while the compressibility tends to increase at a load of 3400–3900 kN/m² which means a gradual reduction of the graph's radius of arc. On the whole, the compression curves C, D and E show the same gently inclination as curve B at a loading value lower than 3400 kN/m² and the compressibility tends to increase at a load of 3400–4000 kN/m². Thus according to Casagrande (1936:60–64), the preconsolidation pressure of a material can be estimated from the compression graph. The load at which the curve changes inclination is termed the pre-consolidation load, and in general describes the maximum vertical pressure at which the sample was consolidated in nature.

According to Broms (1972:319), the compression index of a normally consolidated clay is about 5–20 %, and of a normally consolidated silt 1–5 %. A material with the composition tested here would have a compression index of approximately 3–7 %.

In situ rock stress measurements

In order to discover whether a relationship exists between the present geotectonic stress field of the gneiss granitic rock mass versus the orientation of the fractures of the rock mass, the direction of the foliation, and the directions of the tectonic zones, the results of in situ stress measurements made in the area were used. Those conditions convey an idea of the relative degree of opening of the horizontal fractures of the superficial rock mass, and the mechanism of fracture development in the area.

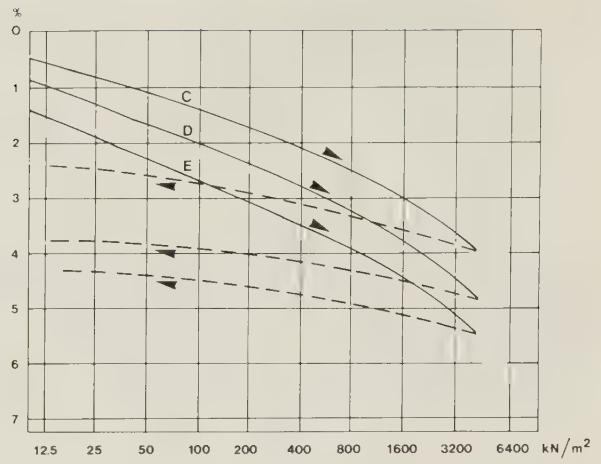


Fig. 63. Relationship between loading and compression. The course of compression in samples from the inlet channel (C), (D) and (E).

Correlation between orientation of fractures and geophysical stresses were treated by inter alios Scheidegger (1976, 1977) and Kohlbeck and Scheidegger (1977). Scheidegger (1977) concludes that stress determinations from joint orientation measurements have yielded consistent results in regions where sufficient data are available. The stress trajectories that were found are at least selfconsistent and seem to fit together with the tectonic features of the area investigated. The influence of the present rock stresses on the hydraulic conductivity has been described e.g. by Cooke (1973), Holditsch and Morse (1976), A. Carlsson and T. Olsson (1978a, 1979b, 1979c) and Olsson (1979). The stress-dependence of the hydraulic conductivity in horizontal fractures in petroleum reservoirs was pointed out by Cooke (1973) and Holditsch and Morse (1976). A comparison of the directions of the different hydraulic conductivities with the state of stress in the rock mass were reported by A. Carlsson and T. Olsson (1978a) and they demonstrated that there is a correspondence, as regards the direction, between the extreme values of the hydraulic conductivity and the compressive stress measured. Almost perpendicular thereto, there is a slight tendency to tensile stress at some measuring-points. Therefore, it is reasonable to assume that fractures striking parallel to the direction of the highest compressive stress are kept open by the low compressive stress on the fracture planes. Analogously, the fractures almost perpendicular to the highest compressive stress are more tight. Thus, the anisotropic behaviour of the hydraulic conductivity is stress dependent.

In order to determine the triaxial rock stresses of the rock mass, in situ measurements were made in 7 drill-holes, as shown in Fig. 64. The method used is described for example in Hiltcher (1974a, 1974b), Hiltcher and Strindell (1976b) and Hiltcher, Martna and Strindell (1979), and based on the method of Leeman and Hayes (1966). It is thereby possible to measure the directions and magnitudes of the principal stresses and by that the three-dimensional stress tensor can be determined.

The measurements of the triaxial rock stresses were carried out in three drill-holes in the area of Unit 3 (Fig.

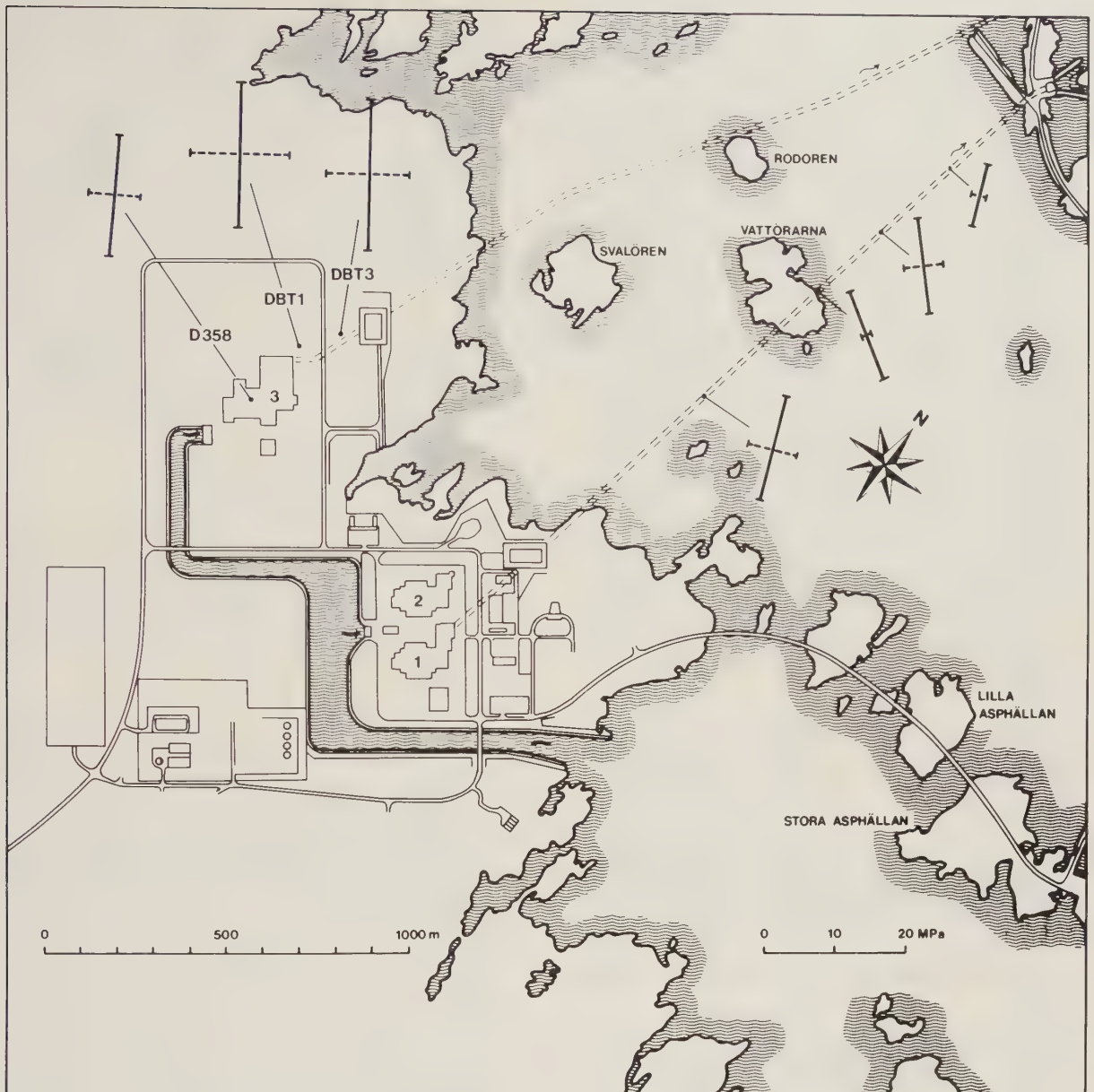


Fig. 64. The mean magnitudes in MPa and the directions of the stresses obtained by measurements in the drillholes DBT1, DBT3, D358, and at four measuring points in the discharge tunnel of Units 1 and 2.

64). In drill-hole DBT 1, the measurements have so far been made down to a depth of about 300 m below the rock surface, while in drill-holes DBT3 and D358, they penetrated down to an approximate depths of 250 m and 30 m below the rock surface respectively. The mean values of the principal stresses in the horizontal plane of each drill-hole are given in Fig. 64. In situ rock stress measurements were also performed in the discharge tunnel of Units 1 and 2. The four measuring points are also marked in Fig. 64, the northern-most being located in the paragneiss area. The measuring points are approximately indicated in the figure.

The principal stresses in the horizontal plane and vertical stress in relation to depth in drill-hole DBT3 are shown in Fig. 65, and Figure 66 demonstrates the principal stresses and the vertical stress measured in drill-hole D358.

Relation between stresses and geological structures in the rock mass

As shown in Figs. 64 and 9 the directions of the highest compressive stresses measured in the area appear to be in accordance with the directions of the two major fracture zones which surround the main construction area. The direction of the two zones is about NW–SE which is also the main direction of the highest compressive stresses of the intervening rock mass. The secondary fracture system in the area has a main direction of N–S with a slight drawing to NW–SE, which means that the directions of the fracture zones of second order are also in fair agreement with the directions of highest compressive stresses. Furthermore there is a clear correspondence as regards the

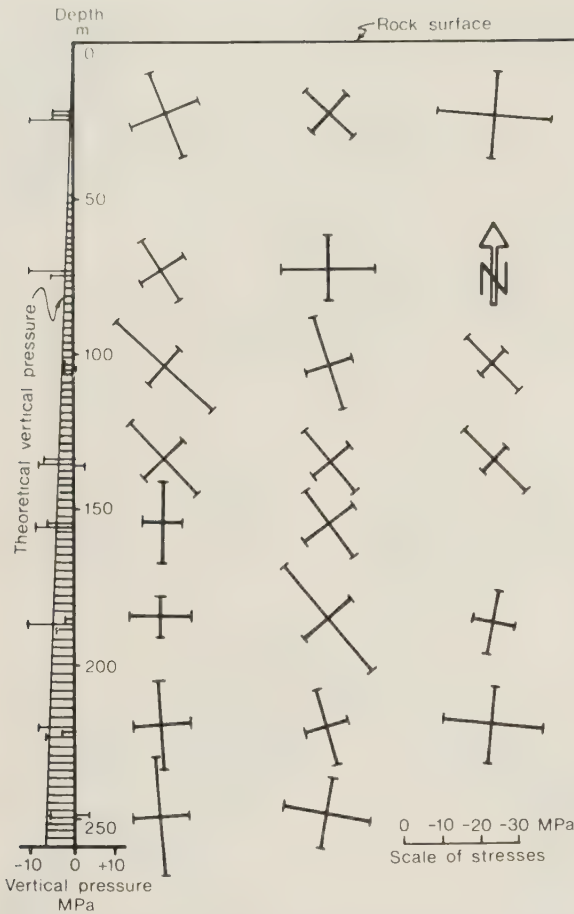


Fig. 65. Principal stresses in the horizontal plane, and vertical stress in relation to depth obtained by measurements in the drill-hole DBT3 (Hiltscher, Martna and Strindell (1979:231).

directions of the rock foliation and the highest compressive stresses.

Joint Set 2, which represents fractures with a strike direction of N18°W–N46°W corresponds to the direction of the highest compressive stress, together with the horizontal set, Joint Set 4, which also contains fractures with a strike direction of NW–SE. Thus the Joint Set 3 representing fractures with a strike direction in the range of N22°E–N49°E shows a direction more or less perpendicular to the highest compressive stress.

According to Hiltscher, Martna and Strindell (1979:231) at the 25-m-level in the drill-hole DBT3, the highest horizontal stress is in the range of 15–25 MPa and has a direction of NW–SE with a smaller horizontal stress of 10–15 MPa perpendicular to the highest initial horizontal stress. The vertical stress is in the range of 5–10 MPa. The principal stresses and the vertical stress measured in the 30-m-deep drill-hole D358 are shown in Fig. 66. The result of the measurements shows a horizontal stress with a main direction of NW–SE, the magnitudes of the horizontal stress being about 15–25 MPa, with a smaller stress perpendicular to it. According to Hiltscher and Strindell (1976b:154), the triaxial stress tensor was not calculated in each measuring point along drill-hole D358 because the gneiss granite showed major residual stresses wherefore the interpretation of the result was confined to stresses in the horizontal plane and the vertical stress.

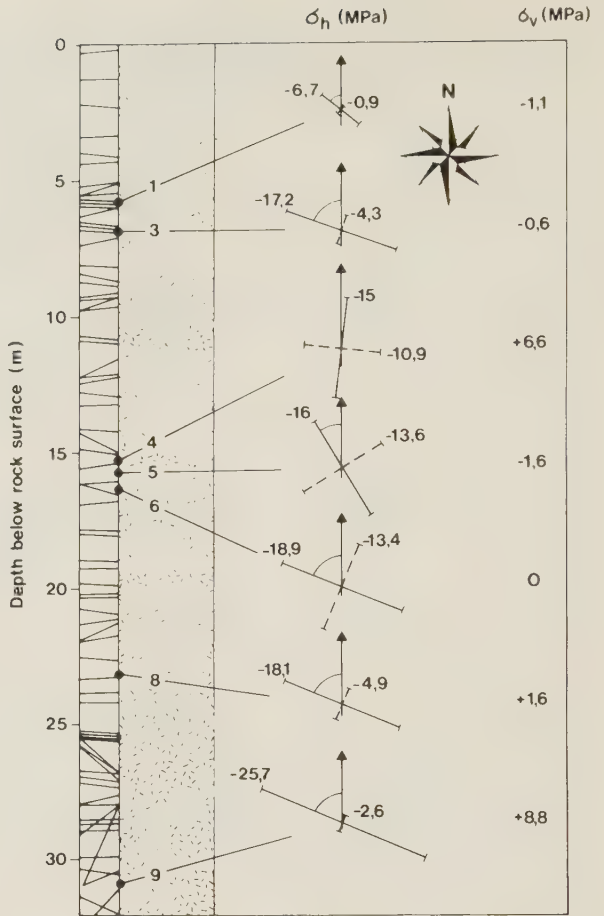


Fig. 66. The principal stresses and the vertical stresses measured in the drill-hole D358 (modified after Hiltscher and Strindell 1976:156).

Hence the rock stress measurements carried out in the investigation area show close correlation between the directions of the highest compressive stress and the fracture zones in the area, the fracture orientation data and the direction of the foliation (Fig. 67). Furthermore, the result of the stress measurements suggest a remarkably high horizontal stress in the superficial part of the gneiss granitic rock mass. Hast (1958) demonstrated a rectilinear horizontal pressure at depth, which at each level is greater than the vertical pressure and maintained that the horizontal principal stresses is on average about 18 MPa at the ground surface and about 100 MPa at a depth of 1000 m, which on the whole means a rectilinear variation of the horizontal principal stresses on depth.

The in situ rock stress measurements carried out at Forsmark prove inter alia that the horizontal stresses are very great in the upper part of the rock mass but also that there is a fairly moderate increase in horizontal stress with increased depth below rock surface.

There seems to be a rectilinear increase in the vertical stress at depth which is correlated with the weight of the overburden. However, new measurements executed at Forsmark which are not yet evaluated show inter alia tendencies to vertical tensile stresses downwards. Thus, this may modify the hypothesis of a rectilinear increase in the vertical stress at depth.



Fig. 67. Stereographic projection showing the fracture orientation data of the rock mass of Unit 3. The stress orientation data and the mean direction of foliation of the gneiss granite are indicated. 1–2. Highest and lowest compressive stresses in the horizontal plane. 3. Foliation of the gneiss granite.

Discussion

This chapter discusses various ideas concerning the characteristics of horizontal and subhorizontal fractures in the Forsmark area, the causal connection of the wide apertures of those fractures in the superficial rock mass, and finally theories regarding the occurrence of filling material of sediments in the uppermost horizontal and subhorizontal fractures in the rock mass. As the investigations related to the superficial rock mass, the present discussion and conclusions refer to the characteristics of this upper part.

Fracture characteristics

The joint pattern within the Forsmark area is composed of three vertical and subvertical sets of joints, namely the Joint Sets 1, 2 and 3 with a strike direction of E–W, NW–SE, and NE–SW respectively, a horizontal set (Joint Set 4) with a strike tendency of NW–SE, and random joints. The grouping into individual sets of joints is based on the orientation of individual fractures and has no connection with the genetic conditions of the fractures.

The gneiss granite in the area shows a well developed gneissosity with a direction of foliation of NW–SE with a steep dip to the north-east. With the exception of the fracture direction of E–W and random joints, the gneiss granite shows an orthogonal joint pattern with a strike direction which is in fairly close accord with the foliation, and a secondary maximum perpendicular thereto. Regarding the dip conditions of the four sets of joints and random joints, the median dip value of the vertical and subvertical sets and random joints is roughly 85°, while the mean dip value of the horizontal set is about 2.5°. As regards the filling material, chlorite predominates in all the sets and random joints, but in the horizontal and subhorizontal fractures the chlorite coating on the fracture surfaces has a

patchy distribution, and filling material of sediments is frequent in the superficial rock mass. There is a considerable difference in fracture aperture between the horizontal and subhorizontal fractures and the other fractures of the rock mass. The median value of the aperture of the horizontal set is about 14 mm and of the other sets and random joints less than 0.1 mm. A common feature in the superficial rock mass is that the horizontal and subhorizontal fractures show apertures of several hundreds of millimetres, and a horizontal fracture aperture of 820 mm was found. The degree of opening of the horizontal and subhorizontal fractures decreases rapidly with an increased depth below bedrock surface and the apertures may be regarded as more or less closed features at a depth of about 5 m though exceptions do occur. Regarding the spacing, the horizontal set shows the smallest of all the sets in the upper part of the rock mass. The result of the drilling operations shows that the horizontal fractures occur at the maximum depth of the drill-holes i.e. at least 100 m down but in all probability also exist at much lower levels. There is tendency to increased spacing with increased depth below the bedrock surface down to a depth of 100 m, but the best correlation between spacing and depth below the rock surface prevails in the upper 30 m of the rock mass. In connection with the measurements of the roughness of the fracture surfaces, there proved to be a slight variation in that the horizontal fractures show a somewhat higher value.

Thus, the investigations made in the area show at several points that the characteristics of the horizontal set are divergent from those of the other sets. As regards the horizontal and subhorizontal fractures there is no appreciable difference in frequency or characteristics between the various sites, but there are local differences along a single shaft wall as well as between individual shaft walls in one and the same shaft. But, in general, the horizontal and subhorizontal fractures and their characteristics are similar in the upper part of the rock mass throughout the investigated area.

On the possible influence of deglaciation on the relative degree of fracture opening

The reason or reasons for the present state of stress in the rock mass are outside the scope of this work and will therefore not be discussed. However it is possible to assume that the land-ice could have exerted a certain influence on the state of stress of the rock mass, especially in the uppermost bedrock. The influence of changes in stress in the bedrock due to the dead weight of the land-ice was discussed by among others Pusch (1974:63, 64, 84, 1978:1–11) and Bergman (1977:12–14, 17–23).

The influence on rock masses and rock mass properties exerted by unloading and stress release may be observed in connection with different foundation activities. Therefore, examples will be given of the behaviour of rock masses due to unloading and loading at foundations of large dams. Moreover stress release in connection with excavations of tunnels will be illustrated. It is important here to emphasize that these accounts are not intended for comparisons with the effect on the bedrock resulting from loading in connection with the glaciation or unloading as a result of the deglaciation. Nevertheless it may be advisable to describe

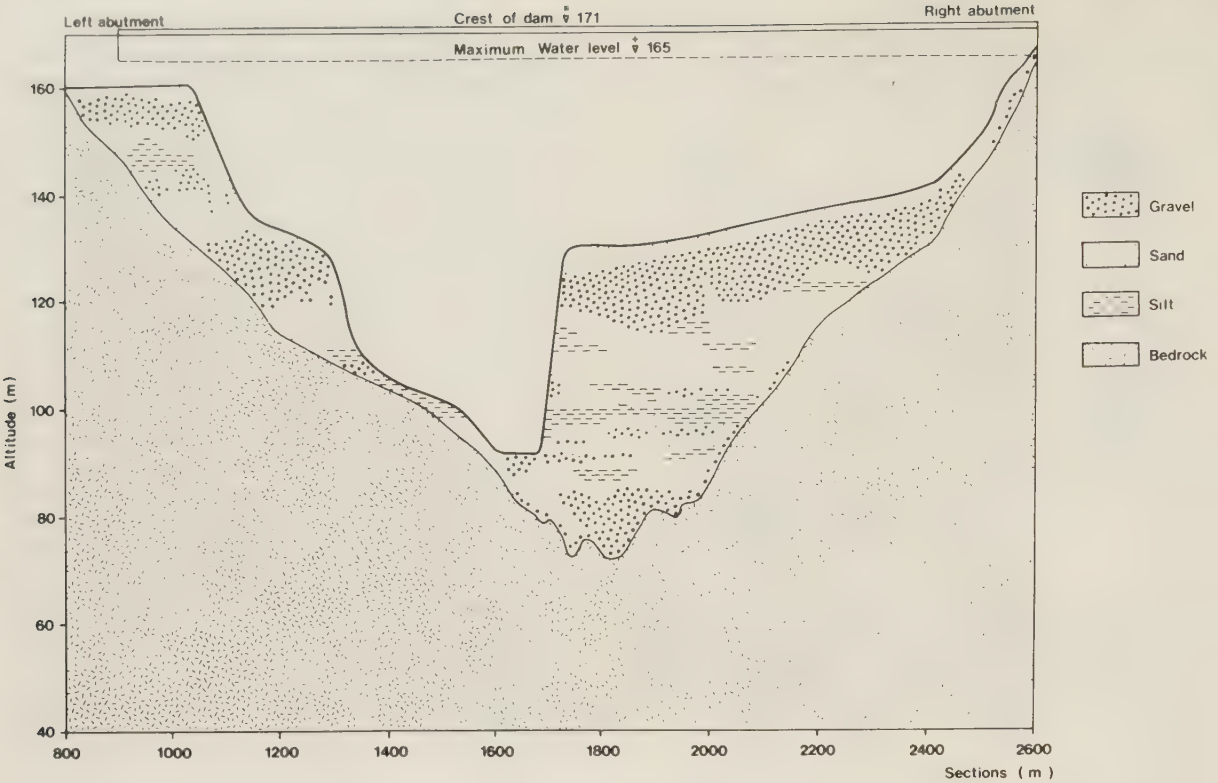


Fig. 68. A longitudinal section of the dam site of the Messaure Dam. Modified after Nilsson, Halvarsson and Bernell (1964:4).

Table 12. Movements in rock of varying quality measured at the Messaure Dam. After Bernell and Scherman (1979).

Section	Quality of rock	Depth of excavation m	Max upheaval of point a mm	Settlement in percent of max upheaval		Total
				During construc- tion period	During opera- tion period 1962–1975	
1500	Good rock	6	80	12	13	25
1719	Fault zone	40	70	57	36	93
1780	Fractured rock	60	90	22	28	50
1860	Good rock	56	95	16	5	21

what will actually happen if the bedrock is first unloaded and then reloaded as in the case of a dam foundation. It may also be useful to envisage the effects on the rock mass behaviour due to excavation for the simple reason that these really can be observed.

Long-term movements in rock foundations beneath the Messaure Dam were described by Bernell (1964), Nilsson, Halvarsson and Bernell (1964), and Bernell and Scherman (1979). The following account of the conditions at the Messaure Dam is chiefly based on Bernell and Scherman (1979). The Messaure Dam, situated on the Stora Lule Älv about 24 km north of the Arctic Circle, is a rock fill dam with a total length of 1900 m. The maximum height of the dam above the rock surface is 101 m and in all, about 10.5 million m³ of filling material were used for its construction. A longitudinal section of the dam site is demonstrated in Fig. 68 with the original Quaternary deposits. These deposits, in all 3.5 million m³, were previously removed because of the risk of leakage and settlement, and the dam was founded on the bedrock, which on the whole comprises gneisses and granites of Precambrian age.

Geological investigations of the dam site have shown that the bedrock consists for the most part of hard granite of good quality, but local zones of weakness intersect the dam line close to the river. These zones of weakness contain crushed rock and some clay material.

The movements were first observed when the filling of the dam was undertaken in 1960 whereupon continuous measurements were made both during construction and after completion. After the excavation of the deposits, the rock mass was grouted in two lines down to a depth of approximately 15 m below the bedrock surface.

An inspection tunnel runs parallel to the dam line shown in Fig. 69; inclinometer holes were drilled upwards from the tunnel roof, the vertical movements a–e were measured at four sections and the movement of the tunnel bottom, f, determined by precision levelling. The result of the measurements is illustrated in Fig. 69, namely those from section 1860. As shown by the curves, the excavation of the overburden caused a vertical uplift of the rock mass, which continued during the first years of the filling period. The maximum upheaval in section 1860 amounted to 95

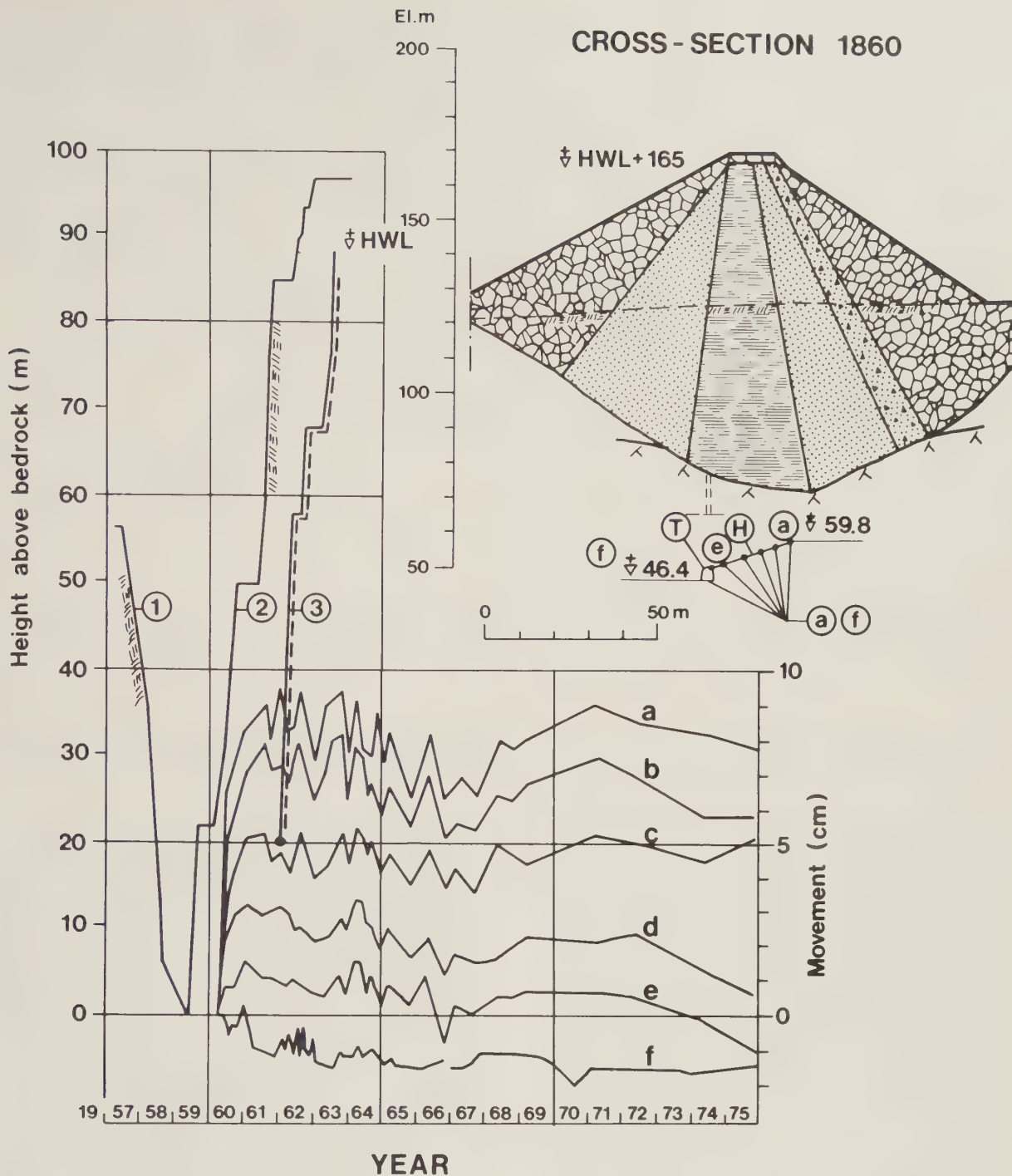


Fig. 69. Movements in the rock foundation of the Messaure Dam. 1. Excavation (m). 2. Dam filling (m). 3. Reservoir level (m). Curves a-e: vertical movement in points (a)-(e) respectively (m). a-f: measuring points. T. Inspection tunnel. H. Inclinator hole. Modified after Bernell and Scherman (1979).

mm, measured in 1962 when the damfill had reached a height of 84 m, i.e. about 28 m above the height of the deposits before the excavation. Moreover the uplift decreased with an increased depth below the rock surface. The only movement which could be observed in the tunnel bottom was a minor settlement of normal magnitude. Thus the figure shows that the upheaval was completed in 1962 whereupon it was being transformed into a long term settlement.

Measuring data from each of the sections with regard to

the movements during the period from the construction stage to 1975 are given in Table 12, while Fig. 70, illustrates the movements in relation to the height of the filling. The result shows that the quality of the rock is of no significance for the upheaval but the settlement is closely correlated with the properties of the rock mass. Furthermore the investigations at Messaure Dam indicated that the filling of the reservoir had a negligible influence on settlement.

Moreover in the event of a comparison between the

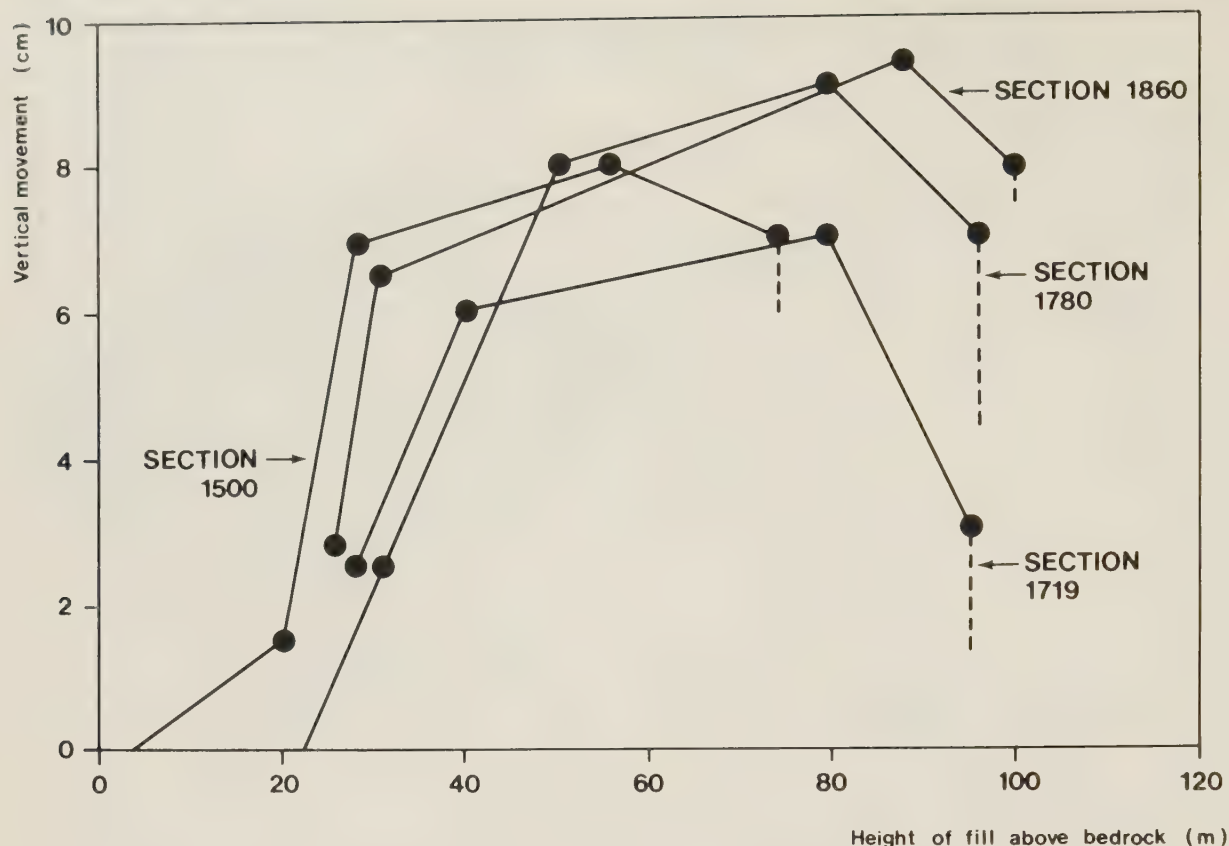


Fig. 70. Messaure Dam. Vertical movements in point (a) of the different sections (cf. Fig. 69). The continuous line demonstrates movement during construction, while the broken line represents long-term settlements during the years 1963–1975. Modified after Bernell and Scherman (1979).

different sections in Fig. 70, the properties of the rock mass appear of importance for the settlement, as also seen in Fig. 71, which plots the maximum movement at different depths below rock surface for the zone of weakness in section 1719 and rock of good quality in section 1860. The curve shows that the transition between the upheaval and the settlement zone is located at a depth of 20 m in the zone of weakness and at 26 m in the rock of good quality.

Other investigations of the behaviour of rock masses as foundations documented an influence on the rock mass due to unloading and loading. Marazio (1966) presents results derived from observations of the behaviour of the foundation of a hollow gravity dam. The results show inter alia that the influence of the horizontal forces is felt down to a depth of 20 m. Kujundzic (1967) points out that for a 120-m-high hollow gravity dam in Switzerland, measurements with plumb lines descending to 50 m showed deformations in high quality rock to this depth. Other examples of rock masses as foundations are given by Terassa, Duffaut, Garnier and Bollo (1966), Weyerman (1966) and Capozza, Penta and Marazio (1966). Terassa et al. (1966), for instance, describe a method of determination in three dimensions of the zones in which the force increases or decreases the apertures of the fractures and hence also the hydraulic conductivity of the rock mass.

These observations of the behaviour of the rock mass in connection with dam foundations reveal influence by various processes. This influence may result in vertical upward movements during excavation, and in vertical downward movements at the filling of the dam. Hast and

Nilsson (1964:607–608) discuss rock stress measurements and their implications for dam building and point out that upward changes in level in an area coincide with the excavation of rock and earth, and the horizontal strata at great depth then suffer a disturbance of their equilibrium. As a result of the reduction in the vertical load, the strata can no longer transfer existing forces, but buckle upwards, and the deformation reduces the horizontal load on the layer, so that the underlying rock strata will tend to take up the released horizontal forces. Furthermore, since all the underlying strata at great depth are subjected to their respective maximum horizontal stresses, the excavation at ground level will set up deep-going changes in the stability of the earth's crust, which will be manifested over a long period as gradual alterations in the level of the bedrock surface. According to Hast and Nilsson (1964:608), the bedrock is likewise depressed when subjected to an increase in the load over a wide area, for instance a dam. They make the essential point that highly complicated movements will probably ensue, if the surface is first unloaded for a period and then reloaded, as during the construction of a large dam, and to some degree in consequence of variation in the water level of a reservoir.

The author himself had the opportunity to witness rock bursting in connection with the excavation of the headrace and recirculation tunnels at Unit 3. During a geological survey of the shallow recirculation tunnel, about 14 m below the bedrock surface, rock slabs about 10 cm in size were suddenly ejected with great force from the western tunnel wall, accompanied by a sound comparable with a

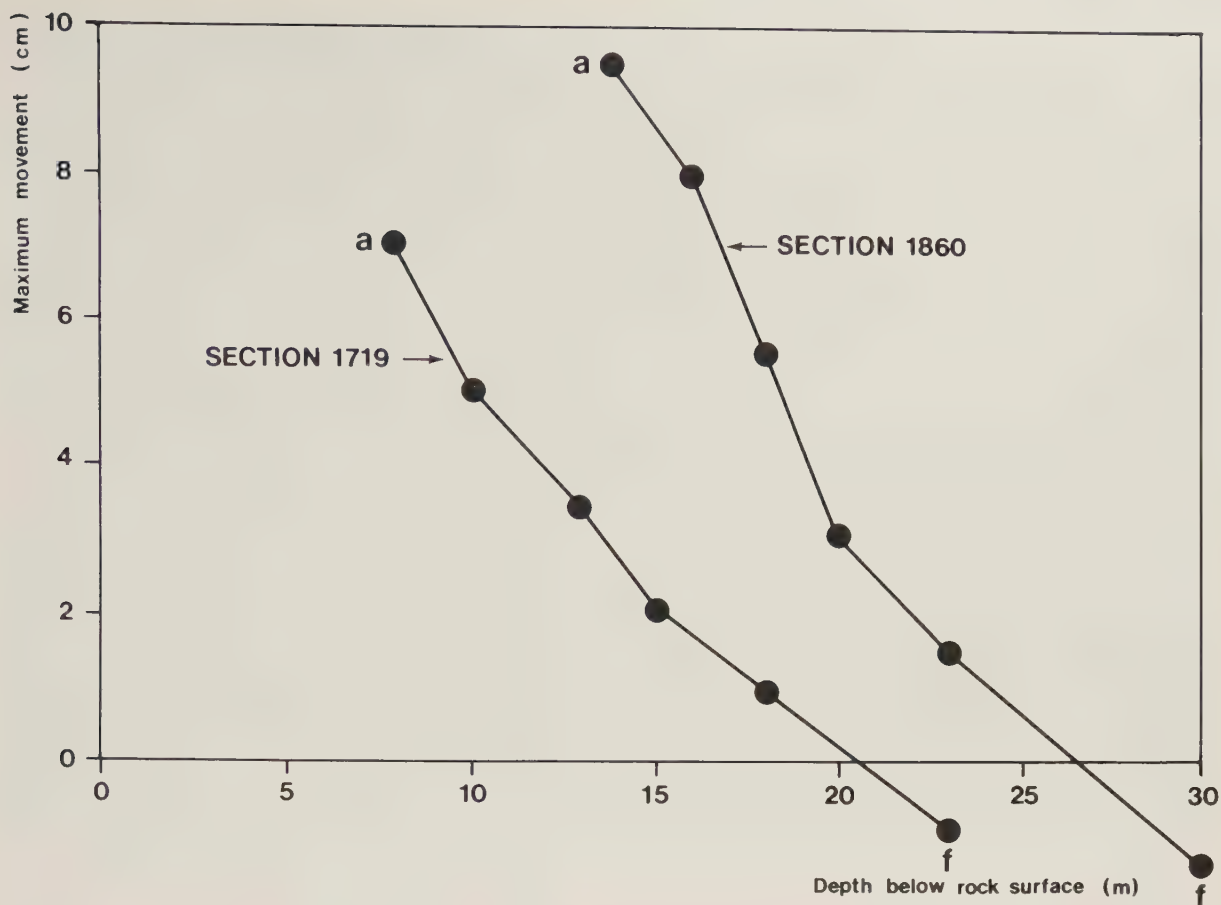


Fig. 71. Messaure Dam. Maximum movement at various depths below rock surface. Modified after Bernell and Scherman (1979).

pistol shot. The same phenomenon recurred in the headrace tunnel situated at about the same depth below the bedrock surface in which this rock bursting also caused problems in the tunnel roof. These phenomena occurred locally in the tunnels, which suggests significant variation of the stresses in the horizontal plane within the area. The rock bursting phenomena in the tunnels were observed about four months after their excavation. Rock bursting was reported by Martna (1970, 1971, and 1972a), who defines the nature of the connection between the tunnel front and rock bursting as that of the necessary time for adjustment. Martna (1970:1137) concludes that the rock bursting in a limited zone of the Suorva-Vietas headrace tunnel was caused by high lateral stresses. The stress measurements in the rock (Hiltscher 1969, Hiltscher and Ingewald 1970a, 1970b and Martna 1972a) revealed large almost horizontal stresses up to 45 MPa and vertical stresses amounting to about 2–8 MPa. Johnson (1970:368) gives examples of stored energy within granitic rocks, which causes sudden splitting or sheeting of granite newly exposed in quarry floors, or scaling of conchoidal flakes from floors or sides of quarries, and the strain energy sometimes being expressed by the formation of diagonal cracks connecting partly completed sheets. Dale (1923) and Jahns (1943) too give examples of this phenomenon.

The long-term loading of the land-ice gives rise to an increase of the horizontal and vertical stresses in the bedrock. As pointed out by Stephansson and Leijon (1979:9), the high primary horizontal stresses may

probably be a consequence of unloading due to deglaciation. According to Bergman (1977:14) the vertical stresses are in the range of 30–60 MPa with an assumed ice cover of about 3000 m and a rock mass of 1000 m. At the melting of the land-ice, the average vertical stress decreases by a value equivalent to the dead weight of the ice cover, but the horizontal stress may not be unloaded in the same manner, because the creep deformation is not essentially reversible. (Bergman 1977:13). Pusch (1974:84) points out that after the melting of the land-ice, the vertical stress would be reduced approximately corresponding to the stress caused by the dead weight of the rock mass, and the horizontal stress would remain relatively unchanged.

A vertical stress of magnitude given above, could thus be expected at a glaciation maximum of a 3000-m-thick land-ice, and a reduction of the vertical stress in connection with the deglaciation down to the magnitude now measured; i.e. less than 10 MPa. The decrease of the vertical stress at deglaciation most probably led to an upward movement because the horizontal stresses persist at a higher magnitude due to creep phenomena. Hence considering the occurrence of horizontal and subhorizontal fractures in the superficial rock mass in the Forsmark area, it may be that the apertures of those fractures, which run parallel to the highest compressive stresses with their fracture planes at right angles to the lowest compressive stress, were widened. The vertical and horizontal fracture apertures would differ in magnitude because the highest compressive stresses act on the vertical fracture planes.

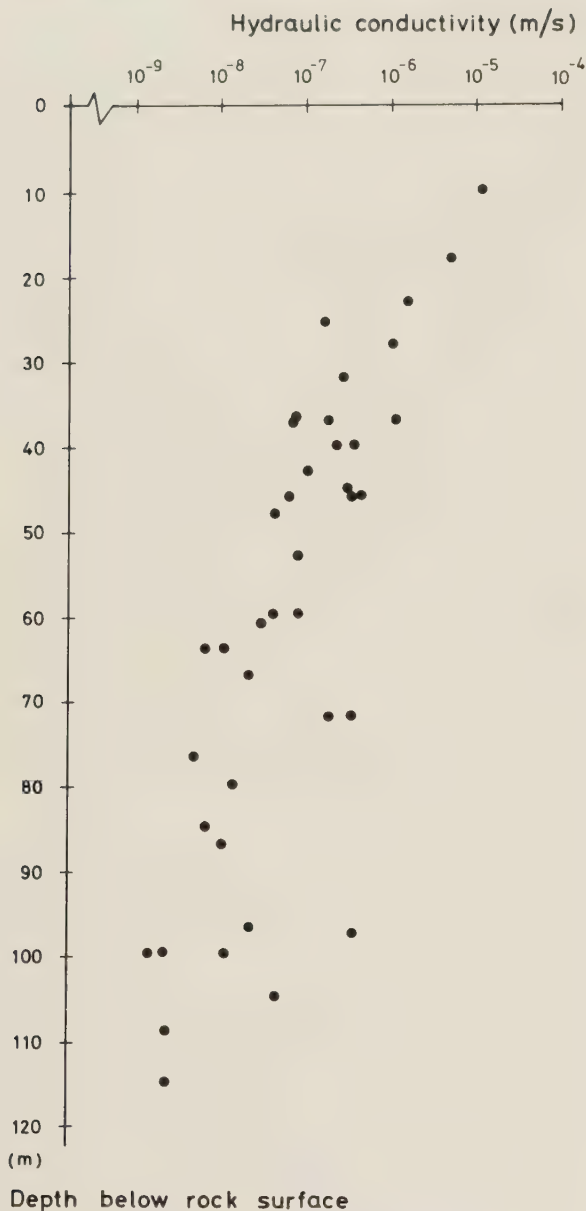


Fig. 72. Hydraulic conductivity values based on data from 39 wells drilled in rock in the Forsmark-Östhammar area. The hydraulic conductivity is given as a function of the well depth (A. Carlsson and T. Olsson 1977b:82).

On the occurrence of sediment filling in the horizontal and subhorizontal fractures

On the basis of the present study of the fracture behaviour of the rock mass some ideas will be given concerning the occurrence of sediment filling in the horizontal and subhorizontal fractures in the superficial rock mass. It is assumed that most of the horizontal and subhorizontal fractures already existed at the time of the last glaciation maximum as small fractures and fracture feasibilities, and that the horizontal fractures were mainly closed due to the vertical load of the land-ice. It can also be confirmed that the state of stress in the bedrock was influenced by the land-ice which may have caused an increase in the horizontal primary stresses and the vertical primary stress.

A change in the state of stress of the bedrock coincided with the deglaciation. The melting of the land-ice caused a decrease of the vertical load and consequently a reduction of the vertical stress. The effects of the reduction of the vertical load may well have resulted in a relative expansion of the existing horizontal and subhorizontal fractures in the uppermost part of the rock mass. This widening was perhaps only severe in the superficial rock mass, for e.g. hydraulic tests made in the area, showed that the hydraulic conductivity values were significantly higher from the rock surface down to a depth of 30 m in comparison with those below this level, while at the ground surface, the hydraulic conductivity is approximately 20 times higher than that measured at a depth of 30 m (A. Carlsson and T. Olsson 1976c:30). Figure 72 illustrates hydraulic conductivity values based on data from 39 wells drilled in rock in the Forsmark Östhammar area.

In consequence of the change in stress at deglaciation blocks and rock fragments perhaps broke loose from the horizontal fracture surfaces. Due to the relative widening of the fracture apertures, the loosened blocks and rock fragments, which frequently occur in the fractures could wedge the fracture surfaces, holding the fracture planes open. This process may have been repeated several times during deglaciation, concurrently with probable regular changes in the stress. In connection with glaciation of an area and oscillations of a land-ice at the deglaciation, and due to consequent changes in water level in connection with different phases of deglaciation, it is reasonable to assume that the bedrock will undergo influences which may result in very complicated movements similar to those reported by Hast and Nilsson (1964:608).

Hence, given a hydraulic gradient this process may promote sediment filling in the horizontal and subhorizontal fractures since the gapped features allow water and sediment material to penetrate. The sedimentary structures in the sediment filling, as also suggested by Stephansson and Ericsson (1975:94), are evidence of deposition by water streaming through the open fractures. The deposition probably happened just inside the ice margin. The material occupied the space between the fracture planes, leaving the fracture apertures to remain in an opened position.

Investigations of the excavated shaft walls in the Forsmark area showed sediment-filled fractures down to an approximate depth of 13 m. Moreover, the sediment-filled fractures are most frequently close to the ground surface down to roughly 5 m. This indicates that the rock mass down to a depth of about 5 m was indirectly affected by the unloading of the land-ice towards the end of deglaciation, but below this level there is no direct evidence of such influence as a result of the land-ice. The probable limit visible at which the rock mass was affected due to the land-ice is clearly demonstrated in Fig. 34. In the uppermost rock mass, the thickness of the sediment filling varies from a few to some hundred mm, and sediment filling almost 900 mm thick is visible in the inlet channel (Fig. 39). Within the entire investigated area, sediment fillings were found in most of the horizontal and subhorizontal fractures in the superficial rock mass, in a few vertical fractures and in some fractures running diagonally between two horizontal fractures. Filling material of sediments were not found below the approximately 5 m down apart from the sediment-filled fracture observed at a depth of 13 m below the bedrock surface in the surge basin at Unit 3. The rare occurrence of



Fig. 73. A shaft wall marked K in Fig. 17 showing intense fracturing along horizontal fractures. Photograph by Göran Hansson/N.

sediment-filled fractures below the 5 m-level could be confirmed by observations in the deepest excavated shafts within the construction area, and by examination of each of the excavated tunnels. The observations also indicated a distinct limit as regards the fracture apertures at the 5-m-level, for below this depth the fractures are more or less closed.

Final remarks and conclusions

Final remarks

A general outline of the present stresses in the superficial rock mass in the Forsmark area is presented schematically in Fig. 67, in which the fracture data and the main direction of the foliation of the gneiss granite are marked. On the basis of the results of the joint survey and of the rock stress measurements, it is reasonable to assume that the fractures parallel to the highest compressive stress, with the fracture planes at right angles to the lowest compressive stress, may be consistent with lateral compression which gives rise to a vertical displacement. The initial development may have other causes however. The fractures which have the fracture planes oriented perpendicular to the lowest compressive stress; i.e. the vertical stress, are represented by the horizontal and subhorizontal fractures.

Hast and Nilsson (1964:606) state that horizontal fractures in the Fennoscandian bedrock developed by lateral

deformation which is consistent with the horizontal stress field in the earth crust, which loaded the bedrock horizontally beyond the limit of its strength and resulted in horizontal fractures due to lateral elongation of the rock in vertical direction. Lateral compression as a probable cause of sheet jointing has previously been adduced and according to Twidale (1973:183) the hypothesis which offers the best general explanation of sheet jointing involving lateral compression induced either through metasomatism, faulting or horizontal stresses, either relict or recent, although he also says that any one of several possible explanations of sheet jointing may be valid in particular areas.

The horizontal and subhorizontal fractures probably derive from small initial fractures which via lateral compression became horizontal and subhorizontal continuous and discontinuous fractures. This is consistent with sheet fracturing in that the sheet fracturing results from enlargement of small cracks and flaws that exist in the granite prior to sheeting (Johnson 1970:369). Mineral coatings on the surfaces on both the vertical and most of the horizontal and subhorizontal fractures indicate that they are old structures, as also stated by Stephansson (pers. comm.). Moreover there is a general tendency for horizontal and subhorizontal fractures to occur independent of all other structures in the rock mass, which suggests a temporal relationship between the horizontal fractures and other structures.

Mörner (1977:11) states that the fracturing of sediment-filled fractures in the Forsmark area probably took place at about the time of deglaciation probably due to the rapid-



Fig. 74. A section of the eastern shaft wall of the inlet channel showing a heavily fractured rock mass in the uppermost bedrock. Photograph by Göran Hansson/N.

ly changed stress and strain situation in the bedrock and, or earthquakes initiated by peak rates of glacioisostatic uplift (Mörner 1978:42–43). However, there are various objections to this theory, apart from the mineral coatings on the fracture surfaces, which prove their age. Wolters (1969), for instance, has carried out a rock mechanical research program with samples from 6000-m-deep borings. His results show that no further deformations could be detected after hauling the material to the surface; i.e. equal to unloading. Deformation measurements during cyclic loading and unloading were also performed indicating that even after 10 000 repetitions, stress and strain occur synchronously. Twidale too (1973:175) discussed this problem, saying that simple triaxial tests show that compression and decompression of essential isotropic materials does not cause fracturing save in special circumstances which are unlikely to be found in nature, e.g. in granitic rocks, which are a very common setting for sheet jointing and in the context of slow erosional unloading. Furthermore, even in anisotropic material, several cycles of compression and decompression can be applied to unconfined specimens without fracturing before, with increased loads, the material ruptures fatigue. In this context, it can be mentioned, that Bjerhammar (1977:4) states that during the ice melting period, we can expect that the rapid uplift will have caused a multitude of severe faults that generated numerous earthquakes. However, the numerous glaciation periods in Scandinavia must have created a fault pattern that is so advanced, that a new

glaciation will have a limited impact on the total fault pattern (Bjerhammar 1977:4).

Mörner's theory (1977:11) that the fracturing of the sediment-filled fractures at Forsmark occurred at about the time of deglaciation may be valid providing small cracks and potential fractures in the rock, which and via changes in the stress and strain can induce horizontal and subhorizontal fractures although probably only in the uppermost rock mass.

Twidale (1973:174) adduces substantial evidence that offloading can induce the formation of relatively thin slabs or sheets of rock close to the land surface. He confirms too that in anisotropic rocks local unloading and unbuttressing gave rise to features morphologically similar to sheet structure. Gage (1966) has shown that offloading can cause the formation of relatively thin sheets of rock close to the rock surface at the bottom of newly deglaciated valleys, while Kiersch (1964) describes development of fractures due to offloading in relation to older glacial and more recent riverine valleys.

At Forsmark, it is possible, that the land-ice exerted an indirect influence on the joint pattern to an approximate depth of at least 5 m. This theory derives from the fact that the rock mass above and below this level presents marked differences primarily as regards the apertures and filling material of the horizontal and subhorizontal fractures. This relation is illustrated in Fig. 34. Below the 5-m level horizontal and subhorizontal fractures do exist but the apertures are more or less closed. The statement that the

joint pattern down to an approximate depth of 5 m was influenced by the land-ice may also be based upon the occurrence of fractures in the form of sugar-cube-rocks adjoining some horizontal and subhorizontal fractures. This type of fracturing is shown in Fig. 73. Moreover, the most superficial rock mass is locally heavily fractured and in principle may be characterized as crushed rock, as in Fig. 74.

The stress release phenomena observed after the excavation of the headrace and recirculation tunnels may cause similar joint patterns along horizontal fractures; i.e. sugarcube rock evolved in the vicinity of the horizontal fractures. Hence, it may be assumed that the land-ice possibly exerted an indirect influence on the joint pattern of the rock mass. If a sufficient difference in stress arises at about the time of deglaciation via a more rapid relaxation of the vertical than of the horizontal stresses, the tensile strength of the rock may be exceeded and failure ensue. Due to the existence of chlorite-coated horizontal fractures, the areal strength of the rock mass may be greatly reduced because the coating cannot transmit tensile stresses (cf. Fig. 25).

It is a common feature of the rock mass that the sediment-filled fractures intersect vertical fractures, vertical fracture zones (cf. Figs 36 and 37) and dikes of pegmatites and greenstones (cf. Fig. 35). Observations of these intersections showed that no horizontal displacement of the sheets or the blocks occurred, which confirms the theory, that the final expansion and deposition of the sediment material must have coincided with the last deglaciation. Otherwise, the sheets or the blocks would have been displaced by the land-ice, a fact which also has been pointed out by Mörner (1978:42). The absence of displacement of the sheets or the blocks thus seems to contradict Stephansson and Ericsson's theory (1975), that the widening of the horizontal fractures in the rock mass at Forsmark is a consequence of freezing of percolating water in the fractures. Such a mechanism for the origin of the open fractures could only operate in a cold climate, e.g. during an interstadial or interglacial period. According to Stephansson and Ericsson (1975:94), the sedimentation of the filling preceded the last glaciation. However it is reasonable to assume that, if the sedimentation of the filling material occurred before the deglaciation, some evidence of horizontal displacement of the sheets would be found. If expansion of the horizontal and subhorizontal fractures was due to freezing, it must have occurred either before or after the last deglaciation. Indeed Harland (1957:10) points out that even in cold regions with deep permafrost, the ground may not be frozen beneath larger glaciers. Glacial retreat may therefore allow the freezing of newly exposed ground, which is likely to be saturated with water, as during an interstadial or interglacial period, in accordance with Stephansson and Ericsson's theory (1975). However, Carol (1947) discuss freezing of water in fractures beneath glaciers, and Yardley (1951) suggests freezing before the arrival of the glacier. At about the time of the last deglaciation, the land surface was lying beneath the sea level which means that freezing was not possible to occur.

Furthermore Stephansson and Ericsson (1975:94) state that the structure, composition and pollen flora of the sediment fillings imply deposition during a Pre-Holocene age, possibly during Early or Middle Weichsel, but such a conclusion as regards the age of the sediments is excluded by

Mörner (1977:11). Further evidence that the sedimentation took place during an interstadial in Early or Middle Weichselian time was offered by A. Carlsson and T. Olsson (1976b). This derives from compression tests of the sediment material, which are also presented in this paper. According to A. Carlsson and T. Olsson (1976b:77), these compression experiments indicate that the material was exposed to a pre-consolidated load of about 3400–3900 kN/m². Since a pressure of this magnitude could not have existed in Holocene time, the degree of pre-consolidation in the material would seem to support the theory submitted by Stephansson and Ericsson (1975). The results of new compression experiments on the sediment material here presented are in full agreement with those reported in A. Carlsson and T. Olsson (1976b). However, it remains an open question whether or not such a conclusion is reliable, since some factors are uncertain, e.g. the properties of the material and the time factor, which present great theoretical difficulties, chiefly because the material properties change with time. Flint (1957:91) demonstrates that a state of unusually great compaction in a sediment may result from the weight of overlying ice but can result also from desiccation.

Conclusions

The relatively high frequency of sediment-filled horizontal and subhorizontal fractures in the superficial rock mass may be an effect of the change in state of stress at the last deglaciation. From observations carried out in the area, it may be stated, that in the most superficial horizontal and subhorizontal fractures, the terminations of the fractures at the bedrock surface seem to be most frequent (Fig. 43). However, termination in the rock matrix seems to predominate in the case of somewhat deeper lying fractures, and is also common in the uppermost rock mass, which would seem to suggest, that fracture development followed existing planes of weakness in the rock mass. This is illustrated in Figs. 26, 38 and 46.

Figure 26 shows a chlorite-coated vertical fracture, intersected by horizontal and subhorizontal fractures. Centre at the right hand limit of the chlorite coating of the vertical fracture, a horizontal sediment-filled fracture appears to divide into two fractures, the lower of which shows a wide aperture and contains sediment material. The original, i.e. the upper, horizontal fracture presents a decreasing aperture and thereby contains a very thin layer of sediment, and close to the left division point none at all. This may indicate that the upper fracture had a higher tensile strength, while the lower fracture had a lower tensile strength and thereby the fracture development followed a plane of lower tensile strength.

Such a division of a horizontal fracture is common, as illustrated in Fig. 38. The figure shows a horizontal, sediment-filled fracture on a shaft wall in the storage basin. A division of the horizontal fracture similar to that in Fig. 26 can be seen just above the wooden frame. Here the original horizontal fracture fades and disappears in the rock matrix, while the extreme apertures continue in the lower fracture. This suggests that the fracture development has followed the planes of weakness in the rock mass.

In Fig. 26 the three uppermost subhorizontal fractures peter out in the rock matrix. Similar termination of

horizontal and subhorizontal fractures can be seen in Figs. 32, 35 and 46. The termination of the fractures in the rock matrix may indicate that horizontal and subhorizontal fractures in the superficial rock mass were induced by small chlorite-coated fractures and potential fractures at the last deglaciation. The fracture development may be a consequence of the unloading of the land-ice, which caused a change of the stress situation in the bedrock. Given a more rapid relaxation of the vertical than the horizontal stresses, it is feasible, that the tensile strength of the rock mass was exceeded, which caused failure. The existence of chlorite-coated horizontal fractures may have caused that the areal strength of the rock mass was considerably lowered, since the mineral coating cannot transmit tensile stresses. This would explain the patchy distribution of the chlorite coating on the surfaces of the horizontal and subhorizontal fractures. Hence it could be alleged that the land-ice exerted an indirect influence on the joint pattern in the superficial rock mass.

The superficial rock mass reveals a distinct difference in fracture aperture between horizontal subhorizontal and vertical fractures. The difference in aperture may be a consequence of changes in stress relation at the last deglaciation.

In situ rock stress measurements yielded a value for the vertical stresses in the superficial rock mass less than 5–10 MPa. Due to the loading of the land-ice at the last glaciation maximum, it is reasonable to postulate a vertical stress of about 30–60 MPa. At the melting of the land-ice, the vertical stresses decreased by a value corresponding to the dead weight of the ice to the recently measured value. The horizontal stresses probably relaxed more slowly, giving rise to greater deviator stress.

The orientation of the horizontal fractures in the rock mass implies that their fracture planes are oriented perpendicular to the lowest and parallel to the highest compressive stress. In consequence of greatly reduced tensile strength due to mineral-coated potential fractures, the stress situation resulted in expansion of the horizontal and subhorizontal fractures at the last deglaciation. This implies too that the fracture development of horizontal fractures in the superficial rock mass and the expansion of the horizontal fractures were contemporaneous; i.e. at the deglaciation.

Physical measurements of the apertures of the horizontal and subhorizontal fractures in the superficial rock mass yielded a median value of 14 mm. The measurements represent the upper 5-m of the rock mass. Hydraulic tests performed in the area clearly demonstrated a decrease of aperture with increasing depth below the rock surface (Fig. 72). Extremely wide fracture apertures are found, as illustrated in Figs. 37, 38, 39, 51 and 58. The existence of wide fracture apertures close to the ground surface, and a rapid decrease in aperture with increasing depth (cf. Figs. 34 and 72) are evidently an effect of unloading at the last deglaciation in accordance with the discussion above. On the basis of the observations presented in this paper, it was not possible to adduce definite evidence of fracture development resulting from the unloading of the land-ice below approximate 5 m down. However it may be assumed that such influence is more far-reaching considering e.g. observations of the behaviour of rock masses in foundations of large dams, which revealed an effect on high quality rock masses of at least 50 m below rock surface.

The distinct difference in the frequency of horizontal and subhorizontal fractures in Figs. 31 and 32 is probably due to significant variation either of the stresses or the rock quality within the area. The two figures represent two sections a mere 20 m apart. A similar variation of stresses is demonstrated in Figs. 43 and 73. These two walls are situated about 130 m apart and, as seen in Fig. 43, very few horizontal fractures occur on this wall. However, a high frequency of horizontal fractures can be seen in Fig. 73 as well as an intense fracturing along horizontal fractures.

Rock slabs on a horizontal fracture surface can be seen to the right of Fig. 25. Considering the high frequency of rock slabs in horizontal fractures, and the sugar-cube-rocks adjoining horizontal fractures (cf. Fig. 73), this may explain the occurrence of the very wide fracture apertures. Fracture development presumably coincided with deglaciation according to the above hypothesis. The occurrence of the rock slabs and fragments in the horizontal and subhorizontal fractures in the superficial rock mass may be a consequence of that the tensile strength of the rock was exceeded and failure occurred. This is based on a sufficiently great difference in stress at deglaciation, and on the existence of chlorite-coated potential horizontal fractures. Hence, the wide fracture apertures may be consistent with a ramification of a horizontal fracture which would explain the extremely wide fracture apertures shown in Figs. 39, 51, 56 and 58.

Repeated freezing and thawing seems a probable cause of these extremely wide fracture apertures. Such a process then coincided with the retreat of the land-ice given that the newly deglaciated area was situated above the sea level. However, at that time, the land surface was supposedly below sea level. Sediment-filled fractures are conditional upon a sufficiently high degree of fracture opening. Accordingly to the hypotheses here submitted concerning the expansion of the horizontal and subhorizontal fractures in the superficial rock mass, most of the horizontal fractures existed as potential fractures in the rock mass before the last deglaciation. Then development and expansion are believed to have coincided with the last deglaciation as a result of changes in the stress situation. This offered a possibility for sediment material to penetrate the fractures; i.e. the degree of opening was sufficiently great. The sediment material may have been deposited in the fractures at the ice margin towards the end of deglaciation.

In consequence of the decrease in fracture apertures with increasing depth below the rock surface, the sediment-filled fractures only occur in the uppermost rock mass, down to a depth of approximately 5 m, with a higher fracture frequency in the top 3 m. The occurrence of sediment-filled fractures down to about 5 m below the rock surface is demonstrated in Fig. 34, and the higher frequency in the uppermost rock mass in Figs. 31, 46 and 47. The occurrence of sediment material in some of the vertical fractures in Fig. 56, accords with the mechanism of fracture development illustrated in Figs. 26 and 38. In Fig. 26 the left hand division of the continuous horizontal fracture is comparable with the vertical fracture containing sediment material in Fig. 56.

Figures 32 and 35 reveal that horizontal fractures intersect dikes of greenstones and pegmatites. Observation of such intersections allow the assertion that no horizontal displacement of the sheets was found. Considering the erosive effect of the land-ice, such a displacement would be

discernible. Consequently the absence of horizontal displacement of the sheets seems to confirm the theory that the horizontal and subhorizontal fractures developed from small initial fractures at about the time of deglaciation, and also that the expansion of fracture apertures, and the deposition of the sediment material coincided with the last deglaciation.

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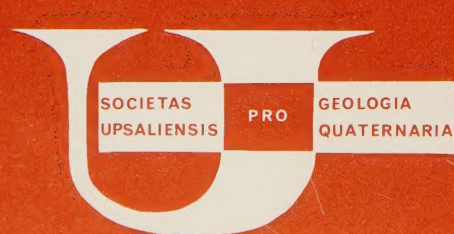
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